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AUTOMATION OF SURFACE IRRIGATION: 15 YEARS OF USDA RESEARCH AND DEVELOPMENT AT FORT COLLINS, COLORADO

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ABSTRACT

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The need for methods of automating surface irrigation systems is greater than ever, because high energy costs preclude alternative irrigation methods with low labor requirements. This report describes the automated surface irrigation systems that have been developed from 1964 to 1979 by USDA in Fort Collins, Colo. Methods of releasing water from both pipelines and open ditches are presented, using hydraulic, pneumatic, electronic, and spring-wound timer control systems. The effects of different automation methods on irrigation efficiencies, as well as energy and labor requirements, are discussed.

KEYWORDS: surface irrigation; automation; irrigation systems; irrigation structures; Fort Collins, Colo.

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Automation of Surface Irrigation: 15 Years of USDA Research and Development at Fort Collins, Colo.

By H. R. Haise, E. G. Kruse, M. L. Payne, and H. R. Duke[1]

INTRODUCTION

The need for reliable systems to automate surface irrigation has become increasingly apparent over the past two decades. When the senior authors began automation research in 1963, the primary concern among researchers was for improved water utilization. As ecological concerns surfaced in the late 1960's, irrigation automation promised further benefits to improvement of water quality by more effective water management. As farm labor became more scarce, particularly with the closing of the bracero (Mexican labor) program, irrigation farmers were forced to seek automation in all farm operations, including irrigation. The inherent capability for automation is a major reason for many farmers to convert to sprinkler irrigation. During 1977 alone, total irrigated acreage in the 17 Western States showed a slight decline (0.9 percent). Sprinkler irrigated acreage, on the other hand, increased by 10.4 percent to 13.4 million acres. In 1977, sprinklers accounted for 27.2 percent of the total irrigated acreage in the West.

Spiraling energy costs beginning in the mid-1970's have caused concern about conversion to sprinkler irrigation. Pressurization of irrigation water to achieve automation through sprinklers results in large capital expenditures and increased energy costs to the farmer, increased logistical problems for energy suppliers, and further dependence of the country on foreign oil.

This paper presents a variety of irrigation devices conceived and developed by the Fort Collins group. Many of these systems have not been discussed in previous publications. Most of the systems have worked satisfactorily, at least under experimental conditions; however, the failures as well as successes are discussed to help others avoid making some of the same mistakes. Developments within each major system are presented chronologically to show the evolution of ideas. As indicated in the "Selected Bibliography" section, others in both research and commercial areas have modified and further developed some of these systems.

What constitutes an automatic irrigation system is questionable. Perhaps such a system would determine the need for an amount of an irrigation, turn water into the field distribution channel, sequence releases until the entire field is irrigated, and then shut itself off — all without human intervention. In this paper, however, we call those systems automatic where the gates or turnouts open and close themselves once the operator has signaled the system to start. Gates that have to be manually closed or reset between irrigations are called semiautomatic.

BURIED PIPELINES

Automation of surface irrigation systems by the former Agricultural Research Service (now a part of the Science and Education Administration), USDA, Fort Collins, began at Newell, S. Dak., in 1963. The idea of automation was conceived at a planning session to discuss the hydraulics of waterflow on a newly constructed bench irrigation system and how the data collected could be used in the design of similar

[1]Soil scientist (retired), agricultural engineer, engineering technician, and agricultural engineer, respectively, USDA-SEA-AR, Agricultural Engineering Research Center, Colorado State University (CSU) Foothills Campus, Fort Collins, Colo. 0523.

flood irrigation systems. A unique feature of the experimental 80 acres under contour benches at Newell was the water distribution system, namely, a buried concrete pipeline with a 12-inch riser and alfalfa valve installed to irrigate each bench. The soil was Pierre clay, and the finished benches were level basins.

USDA Inflatable Pneumatic O-Ring

At the conclusion of the planning session, the senior author remarked that with level-basin irrigation and a closed pipeline distribution system, it should be possible to design a closure that would permit remote control of water released through a standard alfalfa valve for more efficient irrigation and at the same time reduce irrigation labor costs. Several suggestions were offered, but it was not until later that the idea of using a pneumatic diaphragm as an alfalfa valve closure came to mind *(22)*[2]

The first crude pneumatic O-ring was constructed and tested in the CSU Hydraulic Laboratory. It was made from two sheets of nylon reinforced butyl rubber, cemented and double stitched at the edges. The periphery of the hole in the center, through which the threaded stem of the alfalfa lid fit, was also stitched. A hydraulic stand was constructed that allowed testing the valve at heads up to 10 ft. When pressure was applied, air leaked from holes made by the sewing machine in the butyl rubber. Nevertheless, a closure was made, indicating that the idea had merit and that further development was warranted.

Next we contacted Jay Slifer, Watersaver, Inc., in Denver, Colo., who thought enough of the idea to call Dale Parr, production manager at the Carlyle Tire and Rubber Co., Carlyle, Pa. Arrangements were made for the senior author to spend 1 week working with Parr and associates to fabricate an airtight diaphragm.

After a number of attempts, a lay-flat, doughnut-shaped tube was made from rubber, a nylon reinforced butyl rubber cover was made to fit the tube, and an air valve was added. The hole was then fitted with a threaded metal sleeve with jam nuts on both sides to prevent blowout. The inflatable O-ring shown in figure 1 represents the final product produced by the Carlyle Tire and Rubber Co. for the USDA *(26)*.

Pneumatic O-rings were fabricated for 4-inch orchard and 12- to 18-inch alfalfa valves at Phoenix and Poston, Ariz., respectively. We found that regular inner tubes of appropriate size could be substituted for the commercial lay-flat version at less cost. The finished product was not as neat in appearance but was functional. The puckered appearance when deflated may have reduced the discharge slightly, but was quite satisfactory.

The automated orchard valves used to irrigate citrus in the Hall grove near Phoenix (fig. 2) were in operation for 7 years,[3] until the grove was sold. Several of the O-rings failed and had to be replaced, but performance and longevity of components have generally been excellent. Polyethylene tubing connecting the O-rings and controller was laid on the soil surface. The tubing remained usable throughout the life of the system.

At the Bruce Church Ranch, Poston, a buried pipeline distribution system with alfalfa valve risers is used to irrigate level basins on medium-textured soils. Both flat culture to produce alfalfa and small grains and bedded row culture to produce lettuce, tomatoes, and carrots are used. Irrigators work day and night to open and close from four to six alfalfa valves per set every 1 to 2 hr. Approximately 3,000 acres of land are served by the buried pipeline distribution system.

In 1969, a 40-acre site was selected to demonstrate remote control of irrigation on the Bruce Church Ranch, using the pneumatic O-ring closure (fig. 3). The alfalfa field was located at the far end of a main farm lateral that received its water by gravity from a large project canal. The choice of location was unfortunate. We found that in order to irrigate fields in the reach between the canal and demonstration area, the pneumatic O-rings had to be continuously inflated. Leaks developed in the air lines because of poor connections, and, as a result, the air compressor had to run continuously to keep the O-rings inflated. There was no way to isolate the demonstration area when other fields served by the same buried pipeline were being irrigated. The alternative was to remove the O-rings, and replace the alfalfa valve lid after each irrigation to insure positive closure. The manager in charge of irrigation was unwilling to take the time and labor to operate the system under these con-

[2]Italic numbers in parentheses refer to Selected Bibliography, p. 52.

[3] This study was conducted cooperatively with L. J. Erie, agricultural engineer, U.S. Water Conservation Laboratory, Phoenix, Ariz.

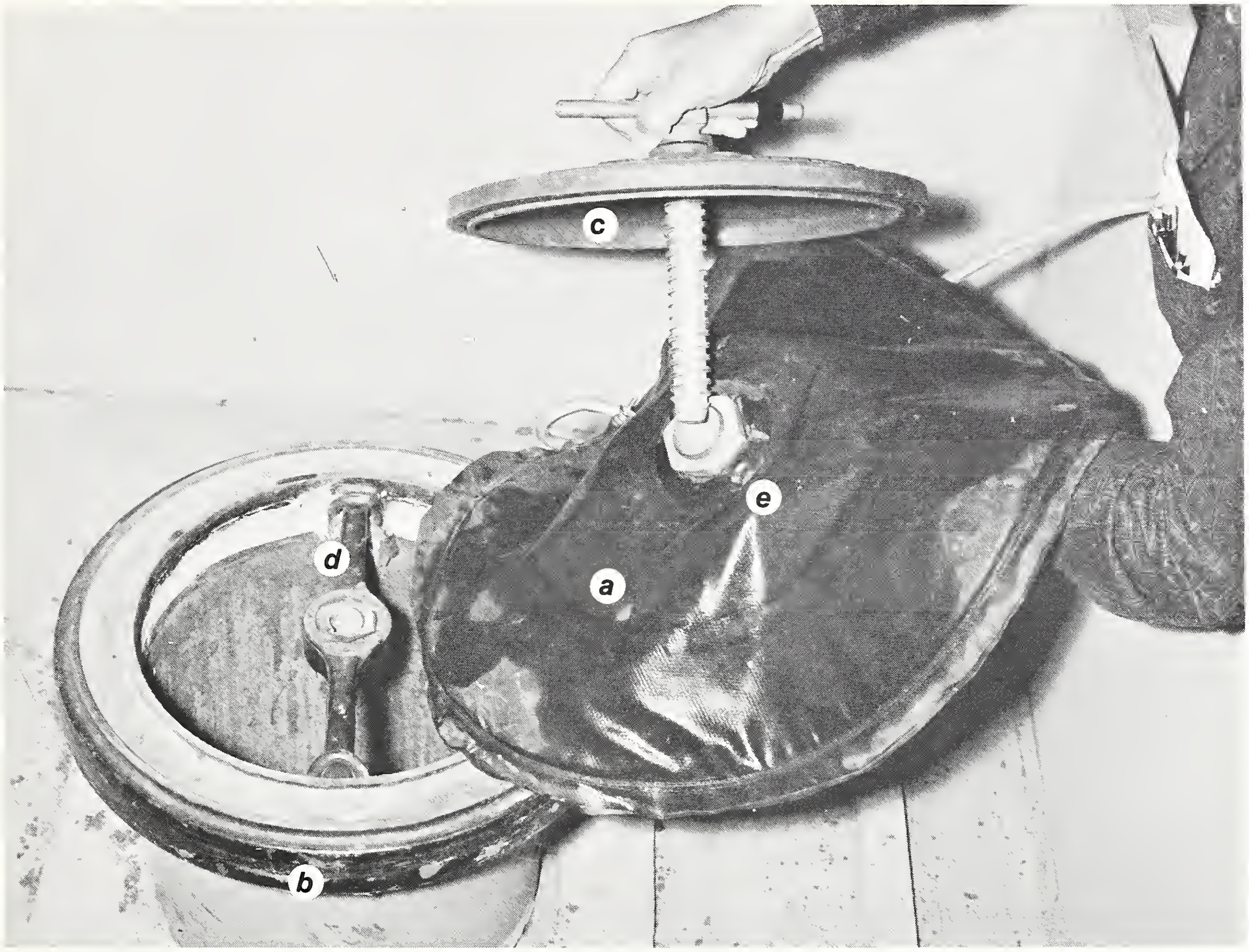

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FIGURE 1. — USDA pneumatic valve *(a)*, showing ease of installation on standard alfalfa valve *(b)*. To install, lid *(c)* is first removed from threaded *(d)* spider. The threaded stem is inserted through center bushing *(e)* and then replaced in threaded spider. Normally open valve provides built-in fail-safe feature in event of air pressure failure.

ditions. Currently available air line components would have prevented this problem.

The lack of acceptance of automation on the Bruce Church Ranch, where ideal conditions seemingly existed, is attributed to the poor site condition indicated above, air lines that were not entirely airtight, and lack of commercially available components and service. This rejection of automation disappointed us, especially since it was conclusively demonstrated that the system and components were reliable and performed as designed. We felt that minor problems that arose could have been solved, but management's lack of enthusiasm led to termination of the demonstration.

O-Ring With Hydrant

One major problem in using the lay-flat pneumatic O-ring in commercially available gated pipe hydrants was its size. For example, the diaphragm had to be 20 inches in diameter for a 12-inch alfalfa valve to achieve watertight closure when inflated in a 4-inch opening between the alfalfa valve lid and valve seat. To aid in inserting this diaphragm into standard hydrants, grommets were placed around the periphery of the pneumatic diaphragm at approximately a 4-inch spacing (fig. 4*A*). Nylon cord was then laced through the grommets so that when pulled and secured to a pin at the top of the alfalfa valve stem, the edges of the diaphragm were "tucked up" around the valve lid. The hydrant could then be attached to the alfalfa valve base. Before adding a gated pipe tee, the cord was flipped off the center pin by reaching through the discharge outlet of the hydrant (fig. 4*B*). This allowed the pneumatic diaphragm to assume its natural position within the hydrant.

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FIGURE 2. — Inflatable O-ring adapted to 4-inch (10 cm) orchard valve in Hall grove, Phoenix, Ariz.

The most recent design of an inflatable O-ring utilizes a cover that conforms more to the shape of the inner tube (fig. 5). Hydrants can be placed directly over the O-ring without the need for lacing, a marked improvement over the original USDA inflatable O-ring. The Colorado Valve Co. has a license to manufacture the newly designed valve under the original USDA patent.

Our first public demonstrations, showing how discharge from a buried pipeline with risers, alfalfa valves, and hydrants could be remotely controlled, took place at the University of Nebraska Tractor Power and Safety Day at Mead, Nebr., in the summer of 1965 *(54)*. The portion of the demonstration shown in figure 6 illustrates how basic components are used to distribute water to furrows using buried plastic-coated aluminum pipe, 8-inch aluminum gated pipe, a portable cast aluminum hydrant, and a laced pneumatic O-ring. All components are assembled above ground for demonstration.

A number of pneumatic O-rings also were field tested at Newell, S. Dak. *(22)*. Radio telemetry, involving the use of coders and encoders of 12 different frequencies, was used to sequence valve openings from one bench to the next. The illustrated layout in appendix figure 1 shows how the system worked. Some problems with radio control are discussed in the section on "Controllers and Communication." Generally speaking, however, the feasibility of using the inflatable O-ring was successfully demonstrated.

A problem in operating the Newell system was caused by the fine-textured Pierre clay, which cracked extensively upon drying, causing problems of piping[4] through embankments on the downslope side of the contour level basins. This turned out to be a serious problem in operating an unattended automated irrigation system. The concept of forming contour level basins on slopes ranging from 2 to 5 percent to conserve rainfall as well as irrigation water created other, more serious problems. Loss of surface soil to form berms or escarpments created fertility and soil physical problems within the level basins. Weed control on the berms was difficult, and special machinery had to be developed for periodic mowing. Imperfect leveling also left low spots that remained wet after rainfall or irrigation. These interfered with timely cultivation for weed control. Although automation works best for level basins, insufficient data are available for recommending such basins on sites where (1) the slopes require large elevation differences between basins, (2) soils tend to crack badly, or (3) growing season rainfall exceeds 6 to 8 inches, for reasons given above.

Another field scale automated demonstration was installed at Wiggins, Colo. *(20)* on a standard buried concrete pipeline with risers and alfalfa valves (fig. 7). Water was supplied with a deep-well pump. The farmer used portable hydrants and 8-inch gated pipe to distribute water to each furrow.

Irrigation sets were made about every 6 hr. At the time, the farmer would have preferred an automated solid set system, that is, enough pipe, hydrants, and O-rings to irrigate fields along the entire 3,200 ft of pipeline. Due to the high cost, however, we compromised on four irrigation sets — enough to provide a 24-hr run. With this setup, the farmer could move one-half the gated pipe and hydrants in the morning and one-half in the evening. This, in effect, provided uninterrupted irrigation of the field. In case of system malfunction where all valves remained closed, a float and cutoff switch to shut down the irrigation pump were installed in the 36-inch standpipe as shown in figure 7*B*.

The most serious problem we had in operating the automated system resulted from an unreliable controller custom designed and built by a local electronics firm. It had four encoders and decoders. The

[4] Seepage of water through connected soil pores or openings — frequently accompanied by erosion.

signals were transmitted by wire placed in a ¾-inch buried polyethylene air line. The problems are discussed in detail under the section for "Controllers and Communication." Improved components and

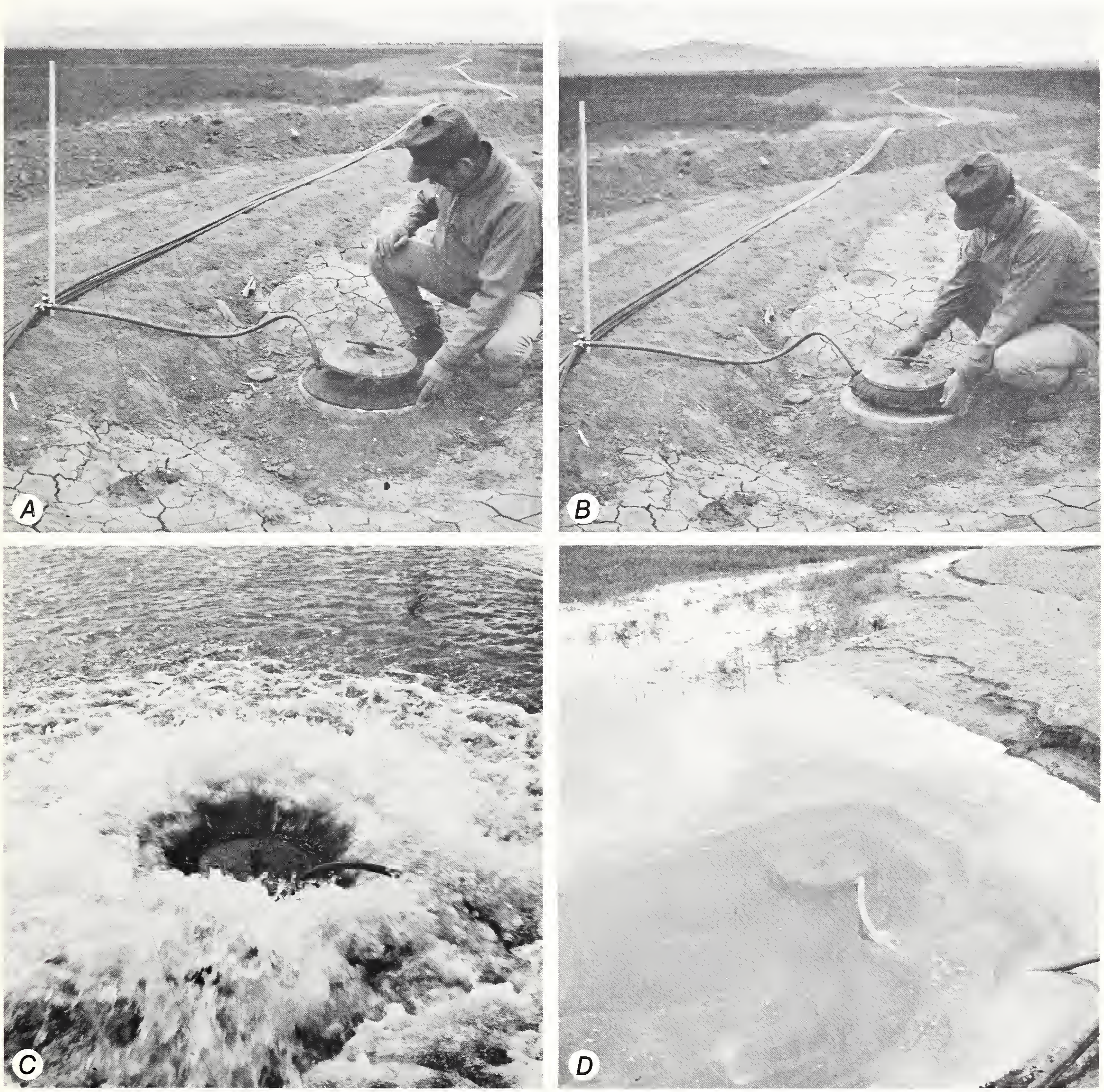

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FIGURE 3. — Field scale demonstration of automated buried pipeline distribution system using USDA O-rings on Bruce Church Ranch near Poston, Ariz. Inflatable O-ring is shown in normally open *(A)* and closed *(B)* positions. Discharge *(C)* is approximately 5 cfs from each riser. Closed valves *(D)* keep 4-inch application ponded in level basin. Alfalfa is grown in 5-acre blocks with zigzag border *(B)*. Four automated alfalfa valves in each "zig" and four in each "zag" flood first the 5-acre block to the left and then the 5-acre block to the right.

miniature circuitry in controllers built since for the same purpose have given excellent results.

Recent commercial developments in Nebraska, under almost identical soil and topographic conditions to those at Wiggins, have shown that some farmers are willing to pay for automated solid set systems where air pressure and pneumatic pillows are used in valve housings for gated pipe like those developed by Fischbach *(12)*. The cost of an average installation is about $130 per acre for a new installation, including buried and gated pipe, automated valves, and controller. Existing systems, with buried

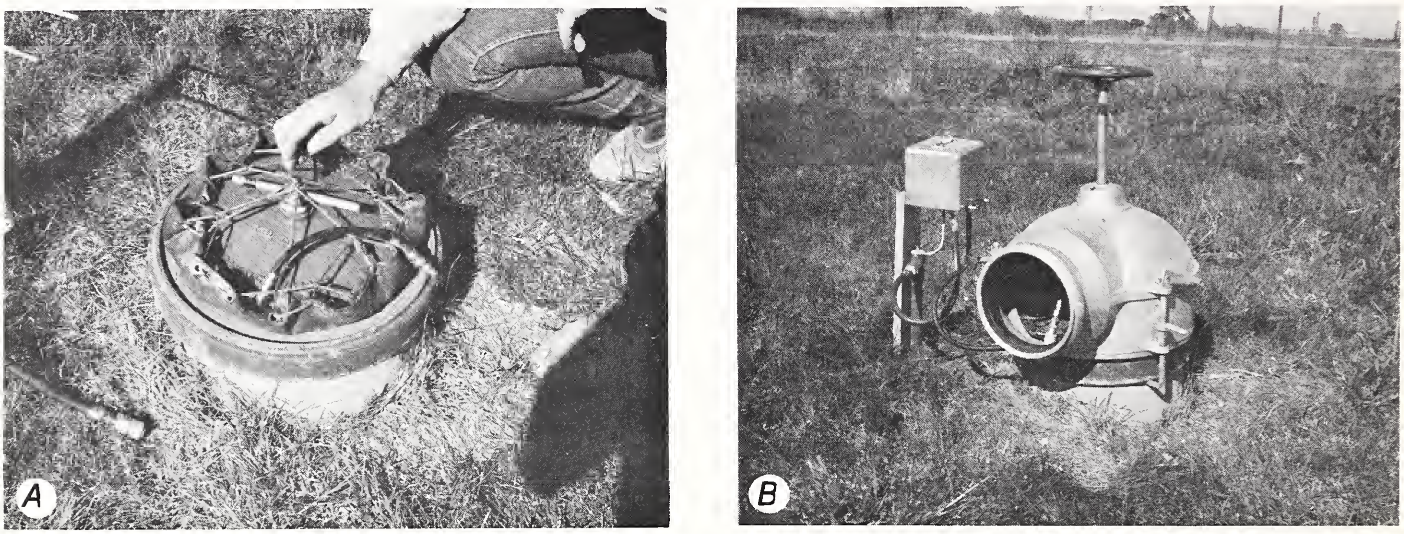

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FIGURE 4. — Valve lacing *(A)* is pulled and secured to pin in top of alfalfa valve stem so that valve edges are tucked up around valve lid. Hydrant *(B)* can then be placed on riser and locked into position. Note the quick-coupler air line secured to pneumatic O-ring and how it is coupled to the decoder and electric relay in box to left of hydrant.

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FIGURE 5. — Newly designed valve eliminates lacing shown in figure 4*A*. Valve is licensed for manufacture under original USDA Patent No. 3320750.

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FIGURE 6. — Demonstration at University of Nebraska Tractor Power and Safety Day at Mead, Nebr., showing how the inflatable O-ring can be adapted to standard alfalfa valves with portable hydrant and gated pipe. Laced O-ring shown in figure 4*A* is inside hydrant in open or deflated mode, allowing water to flow from gated outlets. Control box at right houses the encoder and three-way electric valve used to inflate or deflate the pneumatic O-ring. Farmers here examine and operate section of system where all components, including the plastic-coated aluminum pipeline, normally buried, are above ground for demonstration.

pipe in place, can be automated for $20 to $40 per acre,[5] depending on the length of run.

Pillow-Disk Valve for Risers on Buried Pipelines

The pillow-disk valve for pipeline risers is a modification of the gated pipe outlet valve developed earlier (see fig. 35 in section on "Gated Pipe and Flumes") and is identical in principle to the pipe turnout valve described in figure 17. The valve consists of a movable disk that serves as the valve leaf, a square pneumatic or hydraulic pillow, and a reaction plate fixed to the valve seat (fig. 8). When inflated, the pillow forces the disk against the valve seat, a part of the transition section that fastens the valve to the pipe wall. When the pillow is deflated, water pressure in the riser forces the valve to open. The rigid disk allows use of a pillow smaller than the valve seat if pneumatic pressures are high enough.

The principal advantages of the pillow-disk design are (1) the cost of the alfalfa valve is eliminated (but only at the sacrifice of backup manual control); and (2) strain of cover and inner tube at the center opening of the original USDA pneumatic O-ring is eliminated.

The closure has not been adequately field tested to recommend its use. Trash can be expected to collect at the vertical pipe supports when ditchwater is used. Well water should present no problem. Other investigators have adapted basic components of this valve to hydrants to which gated pipe can be attached for furrow irrigation.

[5] Fischbach, P. E. Personal communication, July 28, 1978. Costs are based on retail prices prevailing in 1978.

Summary

Evolution of the USDA inflatable O-ring began with the tubeless nylon reinforced rubber O-ring stitched at the outer edges and around the center hole; progressed to the lay-flat tube and casing commercially produced; was later modified (lacings added) to accommodate installation in a portable gated

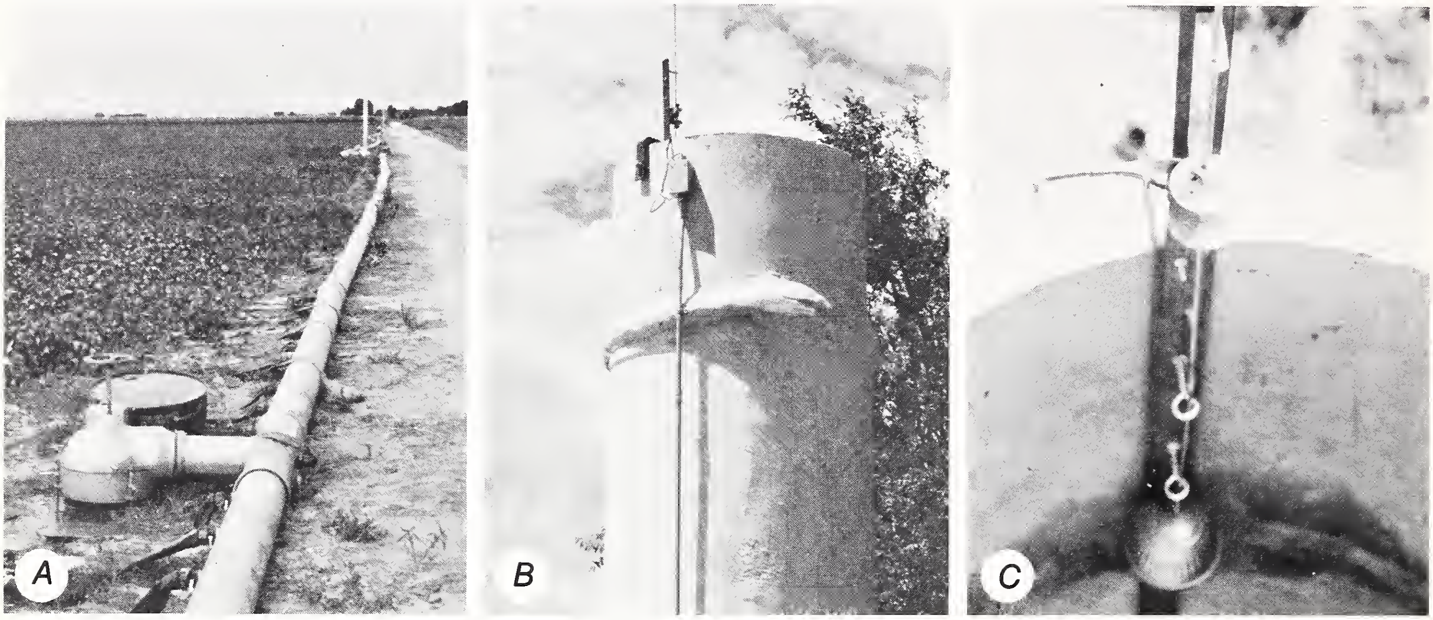

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FIGURE 7. — Field demonstration of automated buried pipeline at Wiggins, Colo., 1966, showing *(A)* portable hydrants and surface gated pipe with Epp-fly valves and "socks" to prevent erosion, and *(C)* fail-safe float switch in *(B)* 36-inch overflow standpipe that shuts off pump if all valves close.

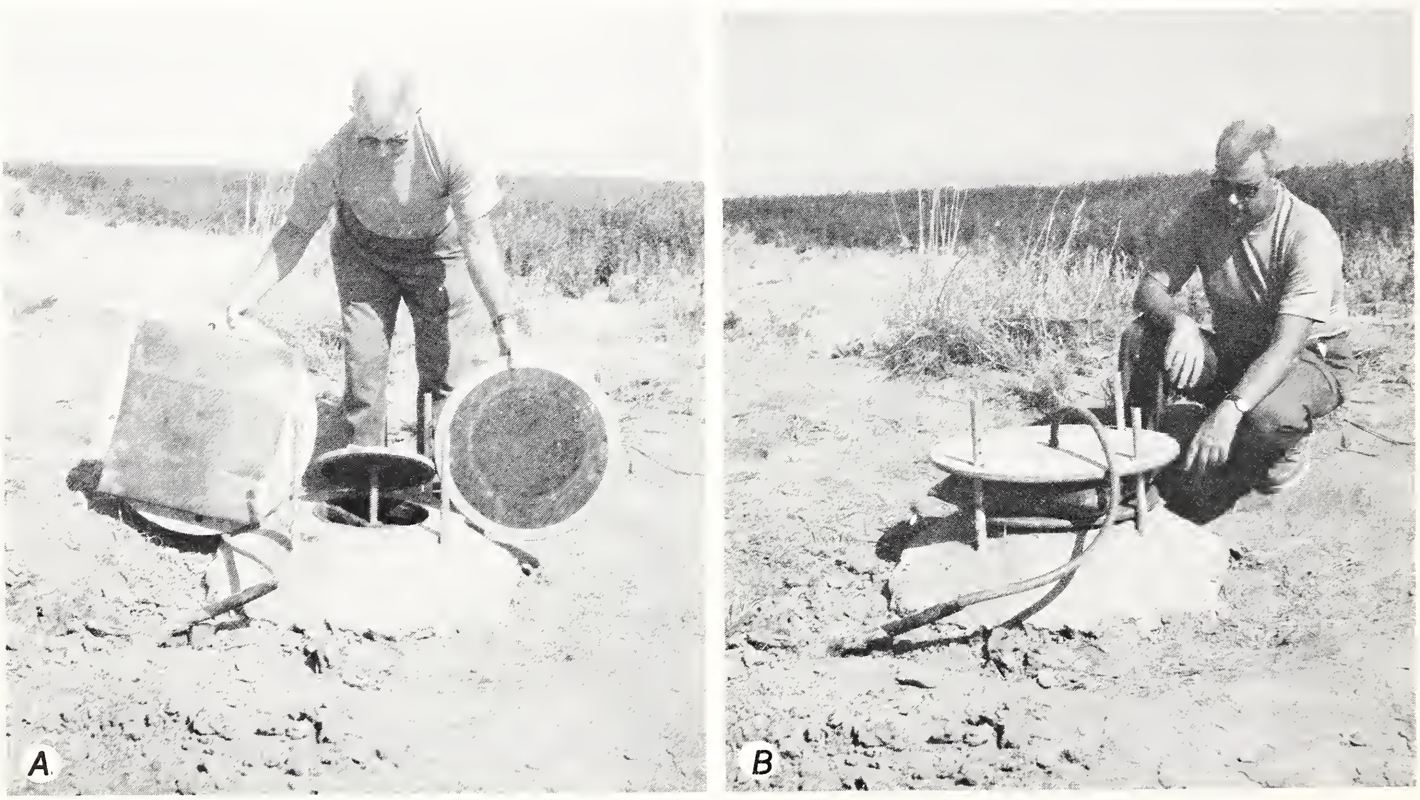

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FIGURE 8. — Pillow-disk valve adapted to pipeline riser. A flat butyl rubber gasket *(A)*, easily constructed, has been added to the disk for improved seal against the original alfalfa valve seat. With pillow inflated *(B)*, gasketed disk is forced against alfalfa valve seat.

pipe hydrant; then was fabricated using a standard inner tube with reinforced butyl rubber cover; and, finally, was redesigned to eliminate lacings and stress at the center where jam nuts held casing together.

Utilization of the pneumatic closures to remotely control water releases from buried pipelines has not been widespread. The greatest activity has been in Nebraska where commercial firms are now making components, installation, and service available. Most installations are on sloping lands, and pumpback reuse systems are achieving field application efficiencies of 85 to 90 percent. At the time of this writing, modified versions of the original USDA valve are available from two commercial companies, including the one in Nebraska mentioned above. A third company is marketing a valve for surface irrigation gated pipe similar to the Snake River Valve developed by Humphreys et al. *(42)*.

DITCHES WITH PIPE TURNOUTS

Many border and basin irrigation systems in the West receive water through pipe turnouts from open ditches; hence, it was a natural step to focus on the problem of adopting closures to turnouts in farm ditches that could convert existing flood irrigation systems to automation. A small portion of the 80-acre experimental irrigation tract in Newell was served by a trapezoidal-lined ditch with concrete pipe turnouts. The turnouts were equipped with standard metal slide gates at the upstream end and were manually operated to irrigate level basins. This distribution system is typical of many thousands of irrigated acres in the West (fig. 9).

Inlet Control

Modified Inflatable O-Ring

Our first attempt to control discharge from pipe turnouts began with a modified USDA inflatable diaphragm installed at the inlet to the turnout (fig. 10). The closure was a modification of the pneumatic O-ring previously described. It consisted of a reinforced butyl rubber cover that encased an automotive inner tube of proper size. The valve lid, a disk blade, was mounted over the turnout inlet. When inflated, a closure was made between the disk blade and concrete channel lining. Laboratory models of the channel cross section were initially made of wood for experimentation. The casing of the pneumatic diaphragm was secured at the outer edges to the channel wall to prevent the pneumatic closure from being sucked into the vortex and then into the concrete pipe turnout as water rushed into the pipe outlet. It was soon apparent, however, that the closure was fraught with many problems; foremost among these was the difficulty of keeping the diaphragm in place in flowing water.

Lay-Flat Rectangular Rubber Valve

The doughnut-shaped O-ring was then replaced with a heavy lay-flat rectangular rubber tube. The leading edge of the tube was secured at the inlet end

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FIGURE 9. — Typical slide-gate installation to control discharge from the distribution ditch through concrete pipe turnouts. Here on the Yuma Mesa in Arizona, citrus grown on sandy soils requires that six to eight slide gates be opened and closed at least every 30 to 60 min around the clock for as long as water is being received from the main canal. The concrete-lined trapezoidal ditch shows heavy chemical deposits from fertilizers injected into the irrigating waters. Automation of these systems can save water and labor by timely operation of outlet structures at any time of day.

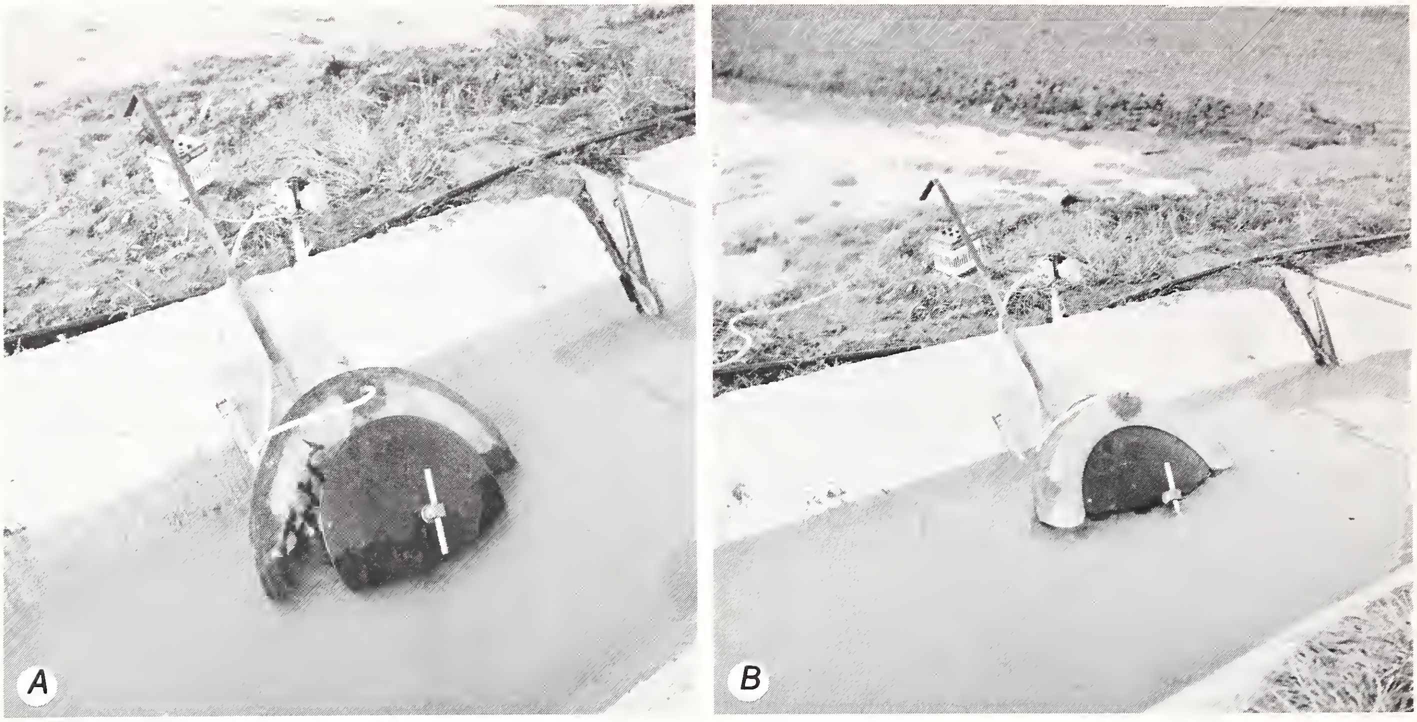

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FIGURE 10. — First attempt to develop closure on inlet of concrete pipe turnout *(A)* in open position; *(B)* in closed position.

of the turnout pipe, using an expandable clamp to anchor it in position. We adapted this idea from a sewer plug manufactured by the Carlyle Tire and Rubber Co. This sewer plug is used to temporarily block the flow of sewage while repairs are made to downstream sections. It is anchored in position with ropes secured to the vulcanized seams that hold the plug in the desired position until inflated. After inflation, wall resistance prevents movement of plug as sewage backs up during repairs. We modified the way this plug was clamped in the pipe (fig. 11). By clamping the leading edge of the tube to the pipe wall, it presented little resistance to flow when deflated and remained relatively trash free.

The lay-flat natural rubber tube was quite flexible and, when inflated, conformed to irregularities in the concrete pipe sections of the turnout. In fact, the laboratory model contained simulated turnouts constructed from both concrete pipe and galvanized corrugated steel pipe. In both cases, the inflated valves created watertight seals (appendix fig. 2).

Flow characteristics through the pipe when the lay-flat rubber tube was deflated were excellent. A garden hose, attached to the downstream valve stem on the tube, extended through the turnout and was connected to an air line buried at the toe of the ditch embankment at the downstream end of the turnout. The configuration of the closure provided essentially trash free operation; however, operational difficulties were seemingly insurmountable. Even though low pressure was required (2 to 3 psi), the rubber tube continued to expand when inflated for extended periods. To overcome this problem, a lightweight reinforced butyl cover was used to encase the natural rubber tube; however, wrinkles in the butyl rubber cover prevented a watertight closure (fig. 12), and flexibility of the natural rubber was lost, which in turn increased the strain on the expandable clamp.

Problems encountered in the field (appendix fig. 2) included rodent damage, excessive wear due to abrasion when inflating, the need for a pilot valve that could rapidly "dump" large volumes of air, and the apparent need for frequent repair and replacement. As a result, research and development were discontinued after 1 year.

Butterfly Valve

Our next attempt to develop a closure at the inlet end of a concrete pipe turnout was to replace the manually operated slide gate in figure 9 with the butterfly valve shown in figures 13 and 14. A hydraulic cylinder activated the valve, using pressurized water. All water was passed through an in-line filter before injection into cylinder to avoid scoring of walls by sand in the water. The butterfly principle minimizes

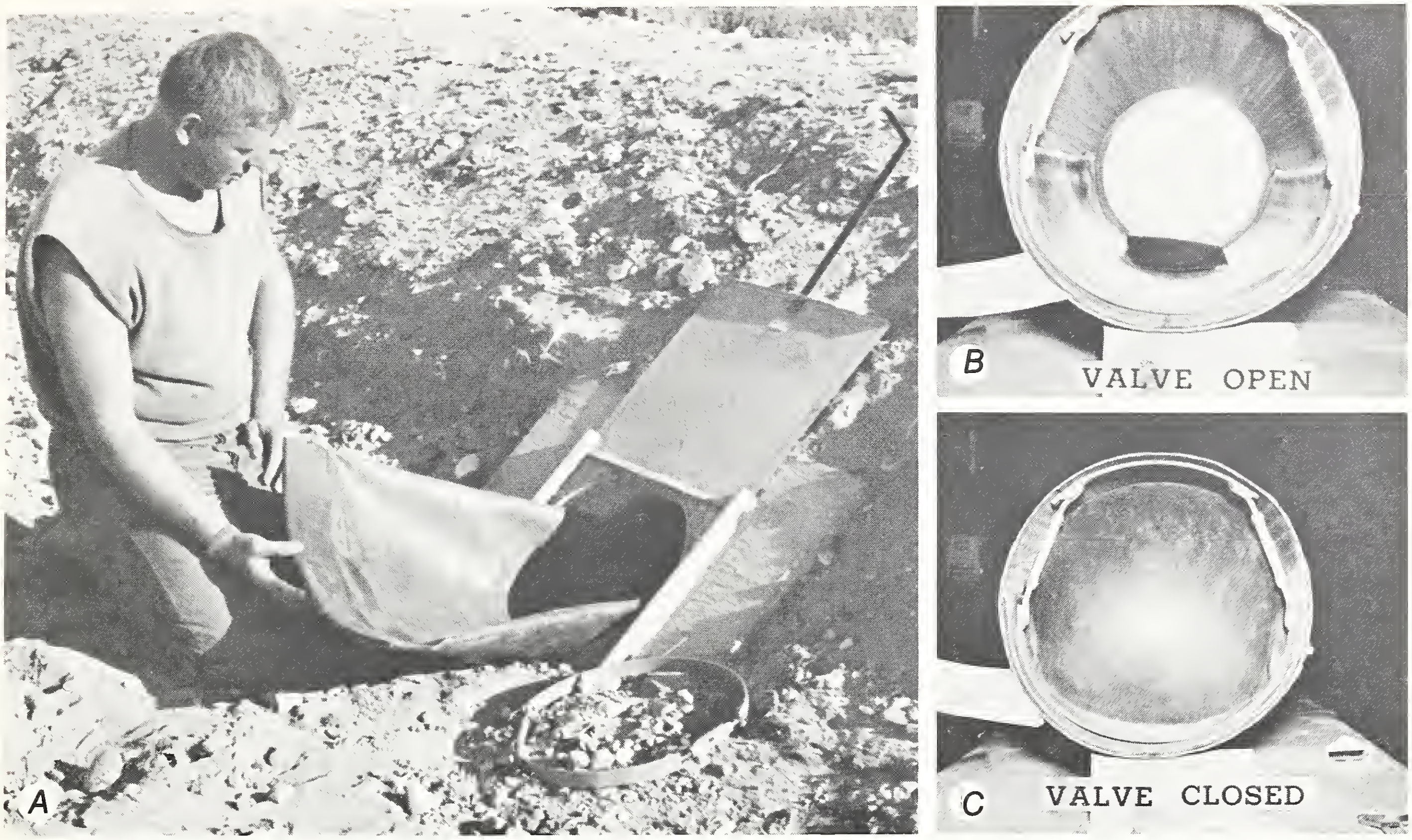

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FIGURE 11. — Installing *(A)* lay-flat tube at inlet of pipe turnout; and pipe model, showing tube in a deflated *(B)* and inflated *(C)* mode, respectively. Note turnbuckles on clamp that allow adjustment needed for expansion within pipe turnout.

torque required for opening and closing; thus, small hydraulic cylinders could be used to keep the cost down.

The heart of the system is a four-way hydraulic control valve assembled from commercial hydraulic pin valves used to irrigate turf. Details on how the four-way valve activates the two-way hydraulic cylinder are given in appendix figure 4. The logic of system operation is diagramed and explained in appendix figure 3. This irrigation system automatically opened the first gates upon sensing presence of water in the lateral, sequenced gates when adequate water had been applied to each border, and released water to a downstream reach of the lateral when irrigation was completed.

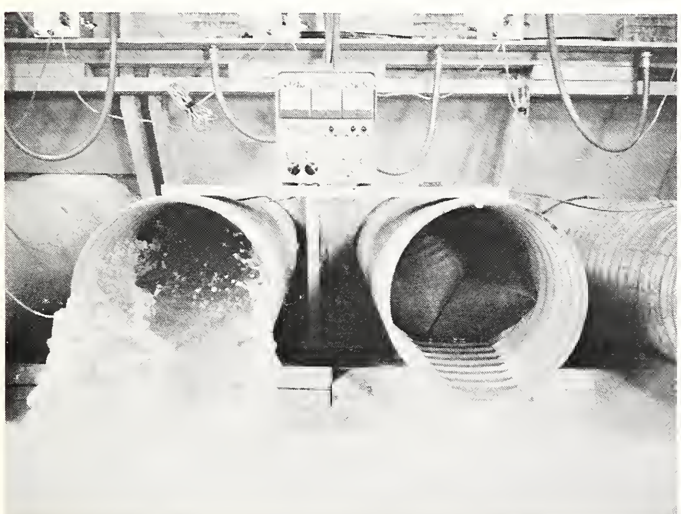

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FIGURE 12. — Model being used to test rectangular lay-flat valve installed in corrugated pipe.

There were problems associated with the operation of this system. Foremost was gopher damage to the ¼-inch plastic communication tubing (appendix fig. 3), which was never resolved. More discussion will be given concerning this and related problems under the section for "Controllers and Communication." We tried to encase the tubing in concrete at a depth of 2 ft using a modified tractor-drawn, subsoil tool, but that was too involved. We also experienced difficulties with malfunctions of the four-way hydraulic valve and corrosion and scouring of the brass cylinders.

At this point in development, we took our problem to Ed Hunter, then vice president of the Toro Manu-

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FIGURE 13. — Replacement of slide gate in figure 9 with butterfly gate and water cylinder (1-1/8 by 6 inches) at inlet to concrete pipe turnout. Note that water cylinder is at top of connecting rod and above ditchwater line to reduce external corrosion from salt in irrigation water (1,000 p/m). Butterfly design produced balanced opening and closing forces for ease of operation. Scale at left of open valve indicates size of components used. Some disadvantages of valve include (1) trash that collected on connecting rod and lever arm; (2) obtaining a permanent, watertight seal between butterfly and steel outlet wall section; and (3) difficulty in opening during hot weather when rubber gasket sometimes adhered to steel outlet section and would not open with hydraulic force available.

facturing Co. He agreed to build a two-way cylinder of durable plastic. Its unique design utilizes differential piston areas to allow complete control of the cylinder with one three-way hydraulic pilot valve (appendix fig. 5). Applying equal pressure to both ports causes greater force on the large side of the piston and the cylinder extends, the excess water being forced back into the supply system. Exhausting the port behind the piston to the atmosphere causes the piston to retract, the excess water being discharged to the atmosphere. This cylinder is compact and, as mentioned previously, has the distinct advantage of operating with a three-way instead of a four-way valve at water pressures up to 50 psi.

Modified Butterfly Valve

A modified butterfly valve utilizing the two-way plastic cylinder is shown in figure 15. A ¼-inch plastic tube that connects the three-way pilot valve (appendix fig. 5) to a standard electromechanical timer (discussed under "Controllers and Communications") permits timed application of water and reliable operation.

The butterfly inlet valve described here had several advantages over the first one used. When the butterfly was closed, the piston was shielded from both light and heat. It was compact. It had no exposures in the channel that caught trash like the connecting rod on the original model (fig. 13). It was nearly watertight. Trash that collected in the cylinder mounting within the pipe turnout caused some problems, but these were not as severe as the problems with the first model. The one overriding difficulty was with freezing. Subfreezing temperatures at Yuma are not common, but we had a cold snap (minimum temperature, 17°F) that did considerable damage to the plastic cylinders. The system was removed after this damage occurred.

"Push-off" Valve

As a final change in design utilizing the two-way hydraulic cylinder, we developed and tested the so-called push-off valve (fig. 16). Here, all gaskets were eliminated with a steel-on-steel closure. The valve was watertight but, like its predecessors, was not entirely trash free. One of the greatest drawbacks was the lack of a fail-safe device when water pressure was inadequate to open the valves. In such cases, the farmer or his workers were forced to enter the water and physically pull on the lids to start discharge. Obviously, such a system does not win wholehearted farmer approval.

Outlet Control

Pillow-Disk Valve for Concrete Pipe Turnouts

Basically, the design for the pillow-disk valve originated with the development of the 2-inch gated pipe valve shown in figure 35. This valve was adapted to concrete pipe turnouts with larger components made from suitable materials and attached to the end of the turnout as shown in figure 17.

Several models were made. The pillow, constructed of nylon reinforced butyl rubber lay-flat tubing and vulcanized at each end, was made by

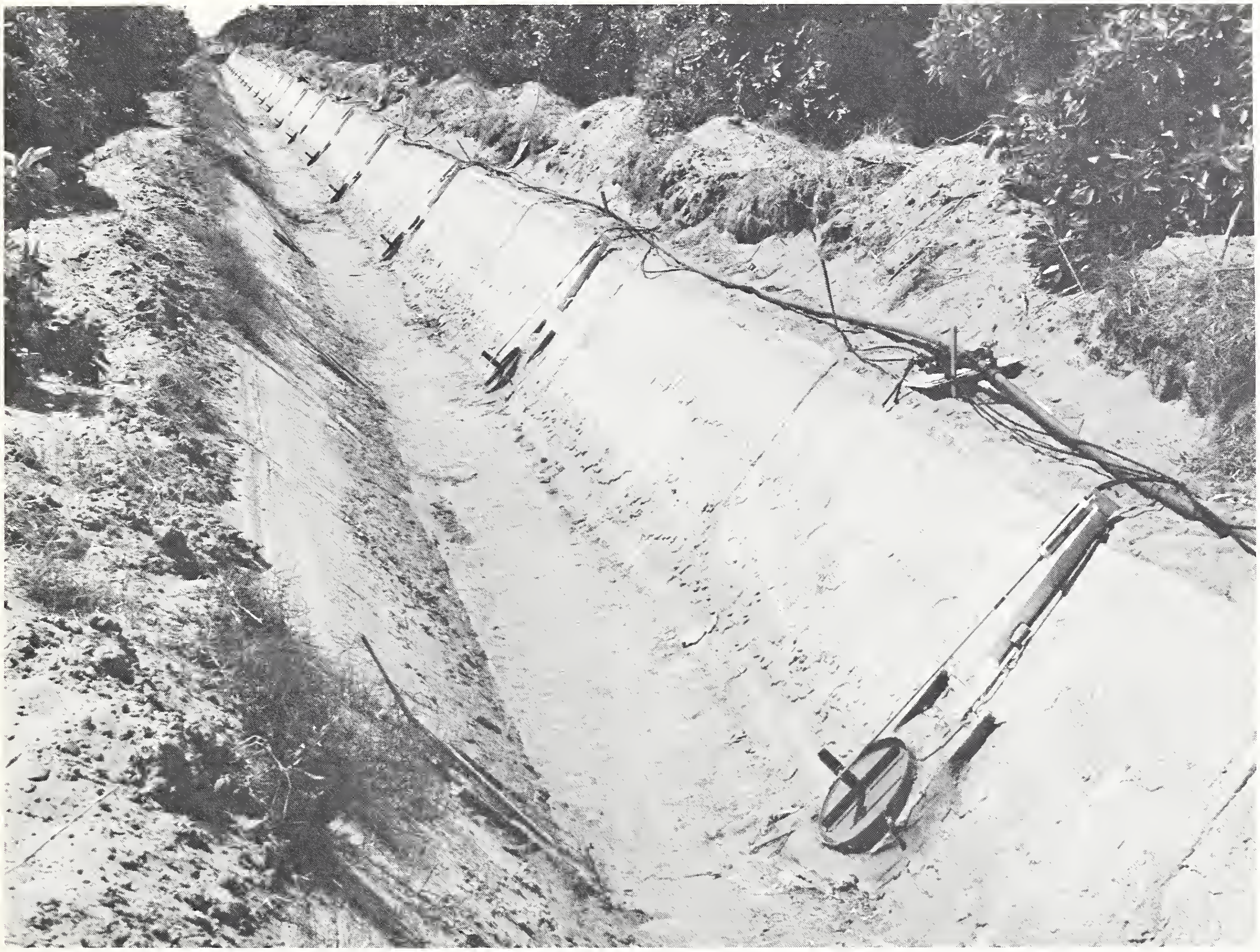

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FIGURE 14. — Automated section of concrete-lined farm lateral showing butterfly valves, water line, four-way hydraulic valve, and small diameter tubing that feed pressurized water to brass cylinders. Citrus is being grown on sandy soils of the Yuma Mesa, Ariz.

Watersaver, Inc. A tractor tire valve stem is vulcanized in the center of the same side as the end folds. The closing disk is made of 16-gage galvanized steel. The reaction plate is attached to the turnout pipe with an annular clamp to which are welded four ½-inch galvanized pipe mounts. These pipe mounts also keep the closing disk in alinement. Holes spaced about 1 inch apart at the end of each pipe mount provide adjustment for the reaction plate to regulate the opening within the limits of pillow expansion. When clamped and grouted in position, some slippage could be detected when the pillow was inflated at 5 pounds per square inch (psi), equivalent to about 190 lb of thrust. Some clamps had to be regrouted when slippage occurred. To provide a watertight seal, an annular galvanized steel ring was made to fit inside the end of concrete pipe turnout. This was grouted into position so that about one-half inch of metal protruded beyond the end of pipe and against which the rubber-faced disk could close. The back side of the pillow pressed against the metal or reinforced concrete reaction plate.

The problem of the clamp slipping when it was placed around the end of the pipe turnout was later solved by Erie and Dedrick *(9)*. Note in figure 17*D* that brackets welded to pipe supports are secured to a steel ring grouted into the end of the concrete pipe turnout. With this design, forces developed by the pneumatic pillow are all constrained by welded or pinned joints whereas the grouted portion need only withstand the pressure-head of water in the ditch. Another improvement they made in an effort to decrease the collection of trash around the pipe supports was to eliminate the bottom pipe mount and in-

crease the distance from the ring to the pipe mounts. The disk in this configuration was allowed to slide back and forth as usual, but was suspended with a bail around the top pipe to keep it in position.

During installation on the Yuma Mesa, an air line was buried parallel to the ditch and between the first and second rows of citrus trees. A chain trencher allowed placement of the polyethylene tubing about 2 ft deep. We believe this kind of placement discourages gopher damage because of periodic flooding from irrigation. Ordinary garden hose was used in making the final connection between the polyethylene pipe and the valve stem on the pillow.

A field installation on the Fisher Ranch near Blythe, Calif., utilized the same pillow-disk closure, pilot valves, and electromechanical controller (fig. 41 in section on "Controllers and Communication") but differed in the manner of air line installations. Use of polyethylene air lines usually requires fittings and clamps, which often leak. It does not take many leaks to keep an air compressor running excessively. On recent installations, we used the newly available polybutylene pipe for air lines. This pipe can be used with either flare-type or compression brass fittings. Although the initial cost is higher, these fittings completely eliminate air line leaks.

At Blythe, we automated four 40-acre level-basin fields used to produce alfalfa and truck crops like lettuce and carrots. Solvent-welded PVC pipe was used for the air line. The "welded" line was then buried in the middle of the access road next to the concrete-lined lateral. Such placement of the PVC pipe was an unfortunate decision. Early tests showed an airtight system was achieved, but with flooding of the access road, a truck got stuck and cracked the air line. Furthermore, air leaks were difficult to locate. Leaks

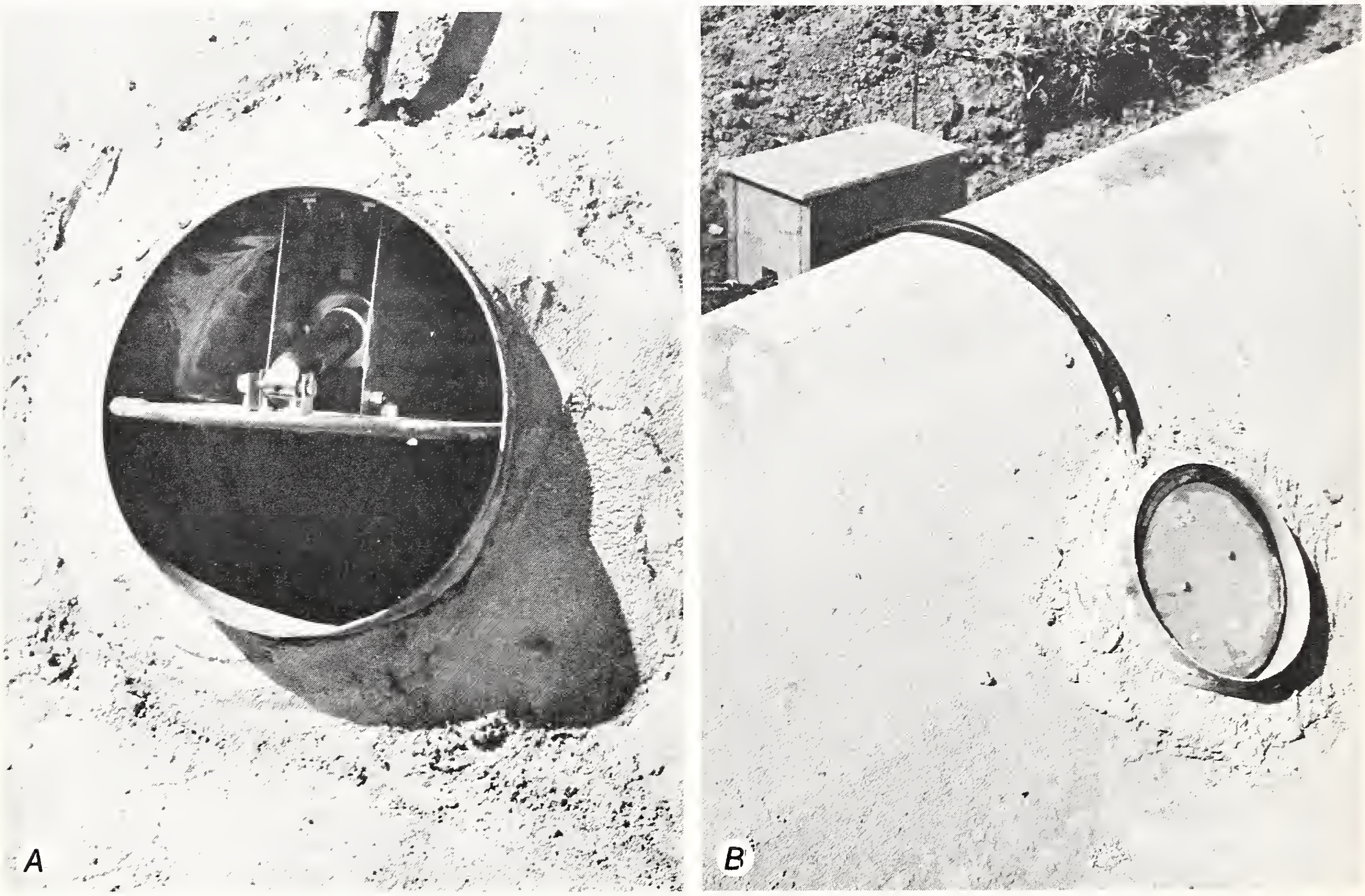

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FIGURE 15. — Modified butterfly gate actuated by "hidden" hydraulic cylinder *(A)*. This modification of the gate shown in figure 13 protected the cylinder from exposure to the extreme heat and ultraviolet radiation in southern Arizona. Normally, the piston was retracted *(B)* giving further protection. All-plastic construction allowed placing the cylinder below the water line without corrosion or encrustation problems. This design was eventually abandoned because (1) damage was caused by freezing, (2) the rubber seal on the gate adhered to the seat between irrigations, and (3) the cylinder force was not adequate to break it free.

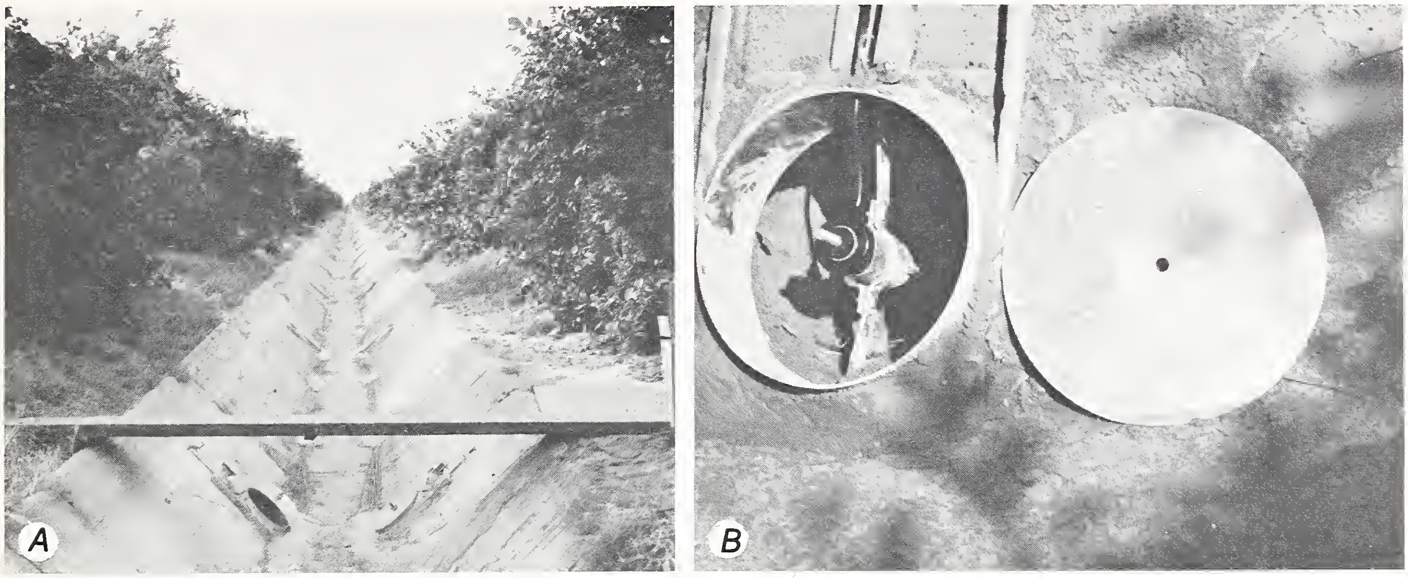

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FIGURE 16. — *(A)* Push-off valves installed at inlet pipe turnouts in same ditch section shown in figure 14. Push-off valve is in open position at left and in closed position at right; and *(B)* valve lid removed to show how plastic cylinder is mounted. Note small plastic control tubes placed in bottom of concrete-lined lateral to prevent gopher damage and to more easily detect air leaks. The plastic tubes are weighted down with small mounds of concrete.

were successfully detected when air lines were pressurized with anhydrous ammonia and located by the odor of the escaping gas. Placement of air lines and protection against rodents and humans are still a problem (see "Controllers and Communication" section).

Placement of pneumatic closures at the downstream end of pipe turnouts can present severe erosion problems unless proper precautions are taken. Leonard Erie, U.S. Water Conservation Laboratory at Phoenix, has developed effective erosion control structures for such purposes *(7, 9, 59)*. Because of the higher exit velocities developed with the automatic pneumatic closures discussed in this section, it is necessary to install erosion control structures.

Figure 18*A* shows a model used to determine flow characteristics and erosion control of a structure that could be precast from concrete. Figure 18*B* and *C* shows the finished product and how the various components fit together at the end of a mocked-up pipe turnout. The forms for this combined pillow-disk valve and energy dissipator were sent to the Fisher Ranch to determine if unskilled labor could fabricate the structure as we had done. Unfortunately, the task was time consuming, and considerable breakage occurred in removing various parts from the form itself.

Having failed with this design, the rancher decided to go ahead with inplace plastered structures like those shown in figure 17*D*. Some of the units, where properly installed, are in good condition today. Others, where set too high or too low or those that had to be placed along the access road instead of along the ditchbank, have suffered from erosion and from being run over by trucks. One constraint imposed by the farmer for future construction was that all erosion control structures had to be out of reach of cultivating equipment and trucks. His comment was that if such a structure could be hit, his tractor operators would do it.

Single, manually opened pipe turnouts are placed about 44 ft apart along the ditch on the Fisher Ranch. Where 20- to 40-acre fields are to be irrigated from one structure, larger outlet structures are required. Figure 19 shows one attempt at adapting the pillow-type closure to a high-capacity structure. This experimental model, also installed on the Fisher Ranch, utilized vertical walls formed from reinforced concrete. Three 16-inch diameter outlets were provided with automatically controlled pillows and closing disks on the downstream end and galvanized metal slide gates (to control rate of water release and to provide manual override if automatic system malfunctioned) on the upstream end. A stilling basin with concrete apron was set 4 inches below the average elevation of the irrigated basin. This basin

effectively dissipated the energy of the water discharged and reduced local erosion to acceptable levels. With a discharge of 20 cubic feet per second (ft^3/s), the depth of water flowing over the 24-ft sill was about 4 inches.

Convoluted Cushion

The final development and current model does away with the butyl rubber pillow by substituting a Firestone Airstroke convoluted cushion that can withstand pressures of 100 psi or more. This high-

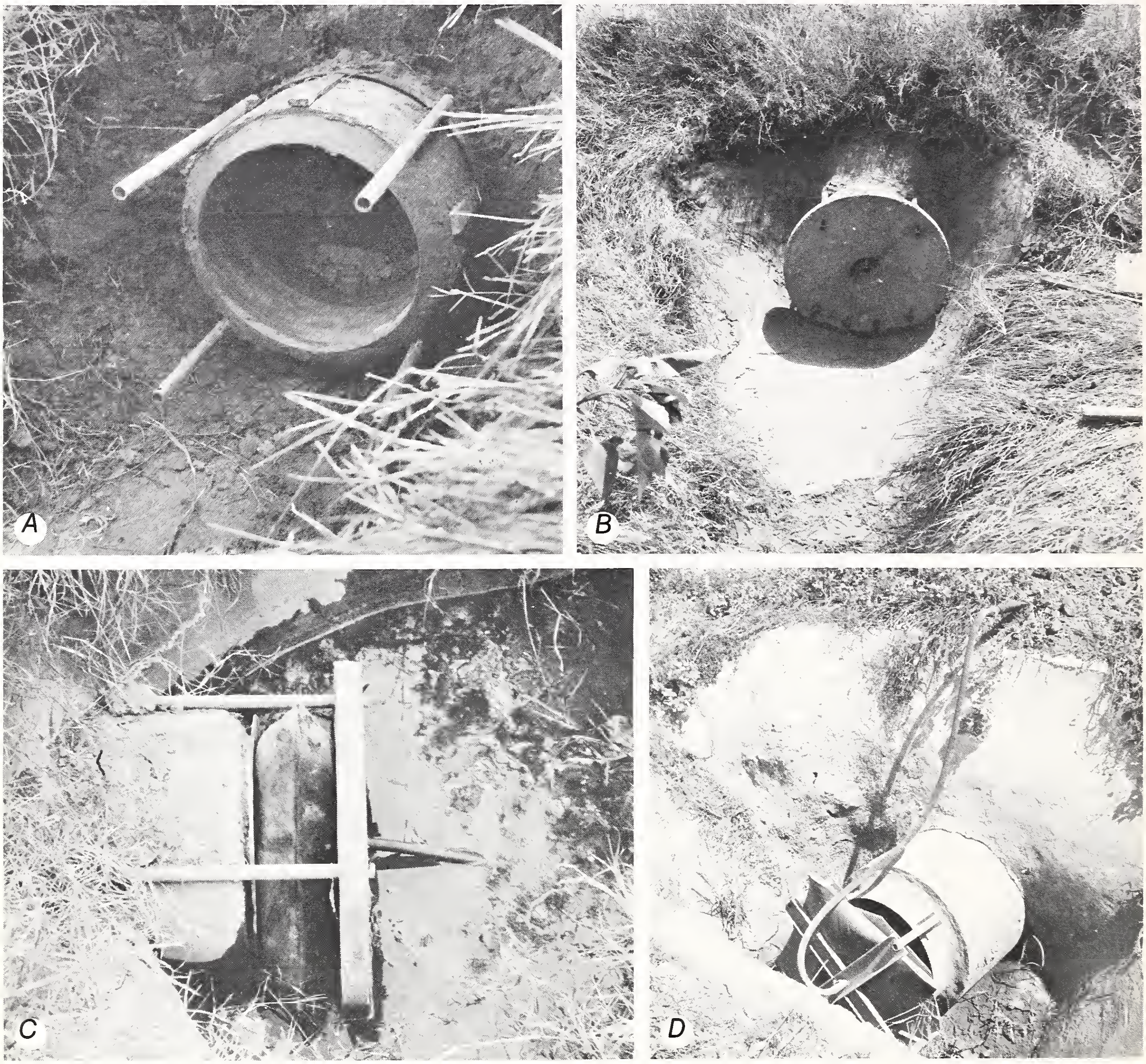

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FIGURE 17. — Installation of pillow-disk valve on an existing pipe turnout. Half-inch steel pipe supports are attached to a steel band *(A)*, which is clamped around the turnout pipe. A reinforced concrete reaction plate *(B)* is attached to the pipe supports. Air is supplied to the pillow *(C)* through the center of the plate, the air line also helps keep the pillow in position. When the pillow is inflated, it forces the galvanized steel disk against a mating steel ring that has been grouted into the bore of the turnout. This design also eliminates the need for gaskets and does not disturb the slide gate at the turnout entrance, allowing manual override of the system if required. *(D)* modification of pillow-disk valve supporting structure eliminates problem of slippage when attached with band clamp. Channels, which replace reaction plate, are welded directly to steel ring grouted in turnout pipe.

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FIGURE 18. — Precast concrete energy dissipation control structure for pillow-disk valve. Model tests *(A)* were used to evaluate performance. Final design *(B)* illustrates components required to add automation *(C)* to an existing tile outlet irrigation system.

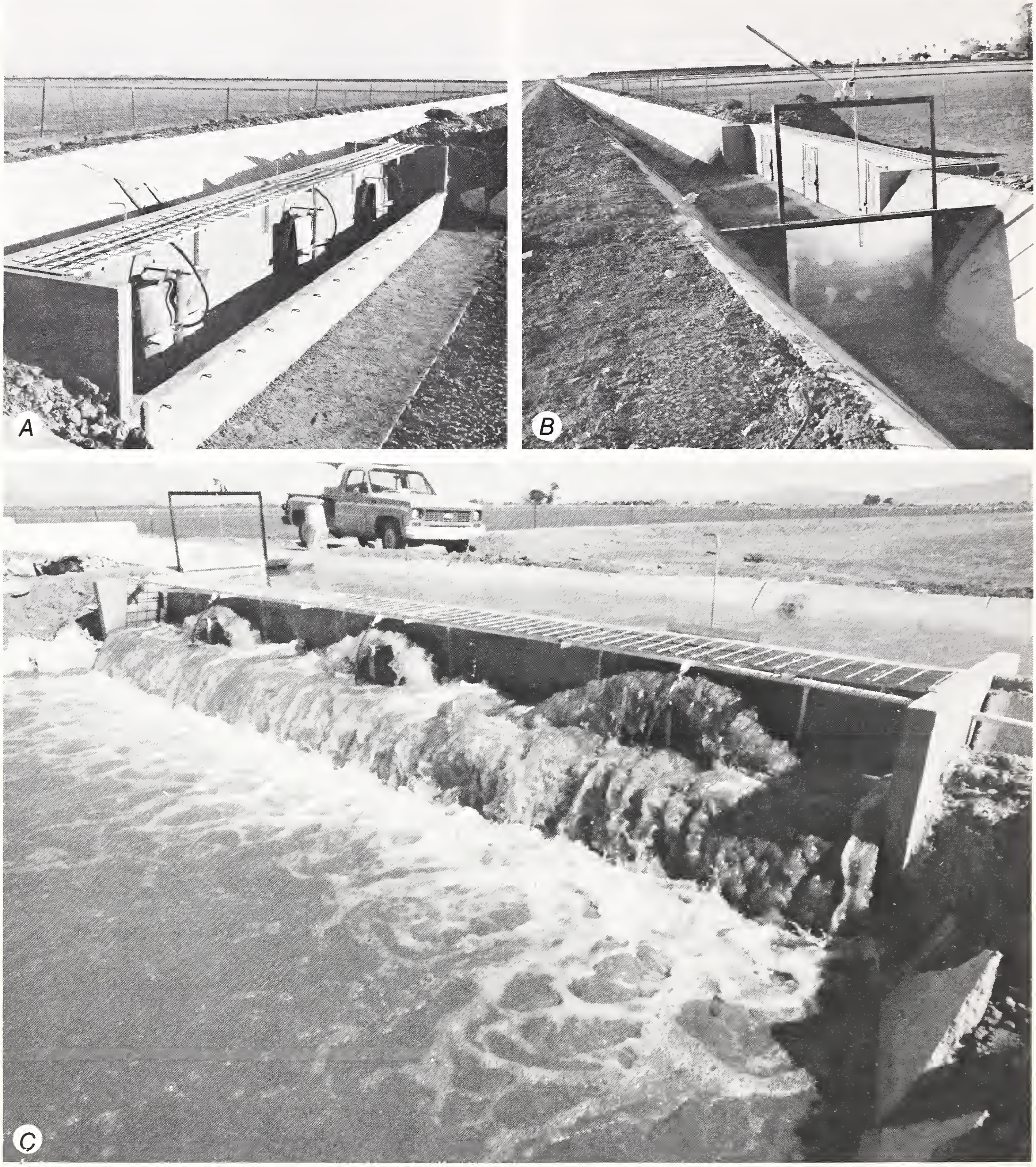

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FIGURE 19. — Multiple outlet pillow-disk turnout installed on Fisher Ranch, Blythe, Calif. Outlet view *(A)* shows energy dissipation structure. Slide gates installed on upstream side *(B)* provide manual backup for the automation system. Discharges of 20 ft^3/s *(C)* were delivered to 20- or 40-acre level basins.

pressure capability allows high closure forces, in spite of the small cross-sectional area, to minimize leakage. In addition, the turnout system is compatible with the pressure requirements for pneumatic cylinders, which may be required to operate check gates in the ditch. The cushions are readily available, airtight, and apparently quite durable.

A variation of this turnout is currently undergoing field tests on the State Home farm near Grand Junction, Colo. This system uses the convoluted cushion with the closure plate described by Erie and Dedrick *(9)*. Because of the corrosive effects of many irrigation waters on steel, we developed and had fabricated, turnout hardware of cast malleable iron. These castings, which have provision for a replaceable O-ring seal, were grouted directly into the wall of a small concrete farm ditch as shown in figure 20. Six level basins being irrigated for experimental purposes receive water from such turnouts. Because the concrete ditch is on a significant grade, three check gates, made of galvanized sheet metal, are powered by pneumatic cylinders.

Donald Benkert (California Dynamics, Inc.) first suggested use of the convoluted cushion and incorporated it into a pivot-type gate with an offcenter locking mechanism for manual override. The experimental model seen in figure 21*A* combines both automatic closure and manual override when necessary. It is attached to the discharge opening on the underside of a trapezoidal section of the lined channel (fig. 21*B*). Placement within the ditchbank protects the gate from damage by machinery.

Summary

Automation of pipe turnouts evolved first with attempts to adapt the normally open USDA alfalfa valve closure to the inlet end of a pipe turnout using a disk blade for the valve lid; then progressed to the lay-flat rectangular rubber tube fastened inside the pipe turnout; then to butterfly valves with hydraulic cylinders activated with a four-way hydraulic valve; and then to butterfly valves operated with a differential area plastic cylinder (Toro Manufacturing Co.) that allowed control with a three-way, instead of four-way, pilot valve. Later, we developed the so-called push-off gate using the Toro plastic cylinder. All of the foregoing were water control devices

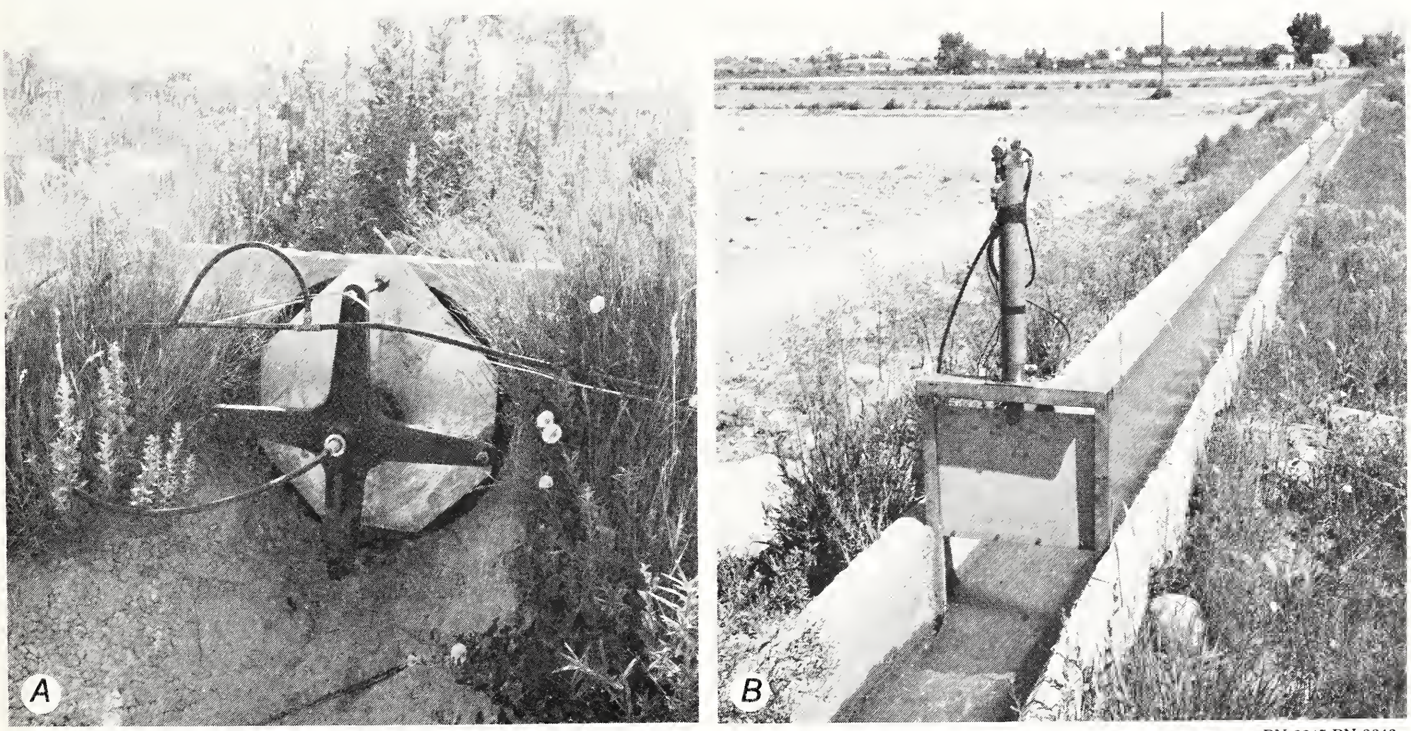

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FIGURE 20. — Pillow-disk automation system installed on State Home farm, Grand Junction, Colo., showing *(A)* cast malleable iron turnout structure grouted into ditchbank. Piston-operated slide gates, made from galvanized steel sheet *(B)*, were installed as ditch checks.

developed and adapted to the inlet of the pipe turnout.

Finally, attention was directed to water control at the outlet end of the turnout. The first closure utilized a pneumatic pillow to force a closing disk against the downstream end of the turnout pipe. Next, the automatic pillow closure was combined with an energy dissipator. Most recently, a Firestone high-pressure convoluted cushion has been substituted for the low-pressure butyl rubber pillow.

Regardless of the type of closure used, the operator must remain alert for operational problems, such as trash accumulation, damage to control lines, mechanical damage to energy dissipation structures, and cracks in the joints of outlet pipes.

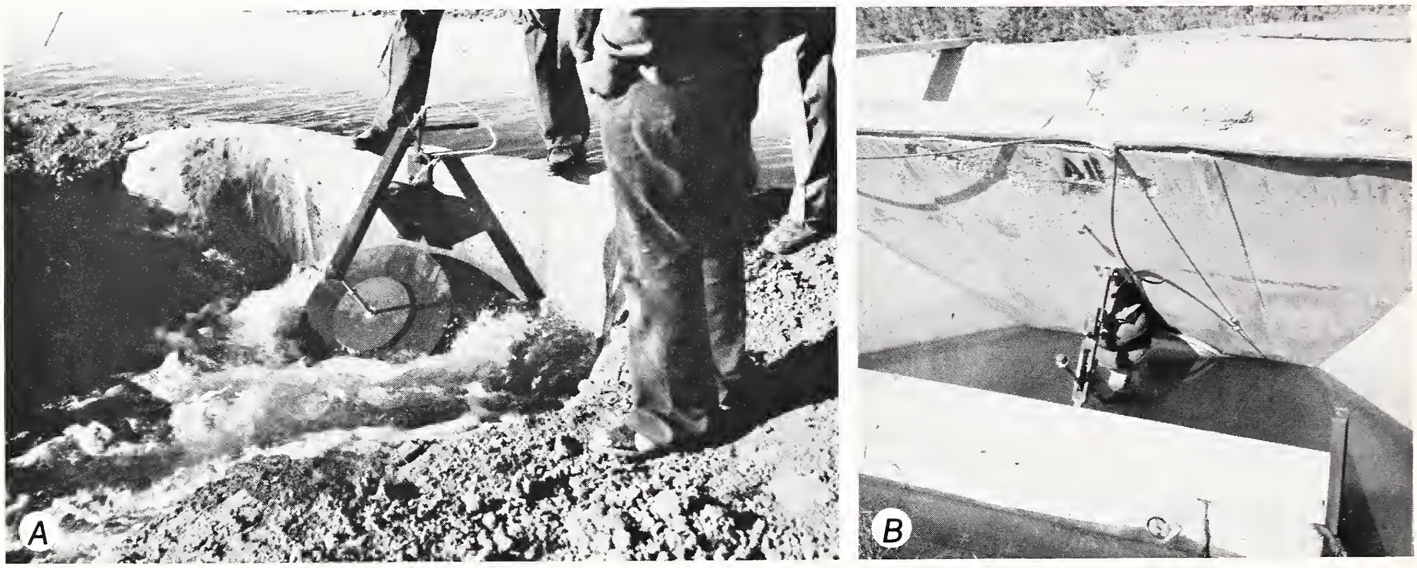

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FIGURE 21. — Turnout control mechanism, utilizing the Firestone convoluted pillow. An early experimental model *(A)* shows the pillow deflated. Presently available commercial models *(B)* use a fiberglass port cover and mount on the underside of a precast section of ditch wall for maximum protection from machinery damage.

DITCH CHECKS AND JACK-GATE TURNOUTS

Our first attempts to automate checks began after a field trip to sugar plantations in Hawaii on the islands of Oahu and Maui. Here, steel slide gates were being hand operated to irrigate so-called level-level irrigation systems *(30)*. We reasoned that some kind of a slide or pivot gate that could be automatically modulated to maintain a specified water depth in a level field supply ditch would save labor and increase irrigation efficiencies. At the same time, excess water in the distribution channel needed to be bypassed to the next downstream check and field supply ditch. A full description of this irrigation system is presented in the above reference.

In the mid-1960's, we began to work closely with Allan Humphreys, agricultural engineer at the SEA Snake River Water Conservation Laboratory in Idaho. Humphreys had been doing a considerable amount of work on drop-open and drop-closed gates, triggered by individual spring-wound timers. Some of these gates were used in Hawaii for sugarcane irrigation and others were used on the U.S. mainland to check water in field laterals. The following paragraphs describe some of the modifications of this type of gate carried out in Fort Collins.

Drop-Open and Drop-Closed, Clock-Operated Gates

The drop-open and drop-closed gate structures developed at Fort Collins are generally semiautomatic, that is, the gate must be reset manually. Then,a timer or other automating device causes the gate to activate (open or close) at the end of a preset specified interval. Labor requirements for such structures are thus somewhat greater than for a more fully automated system. A typical system with semiauto-

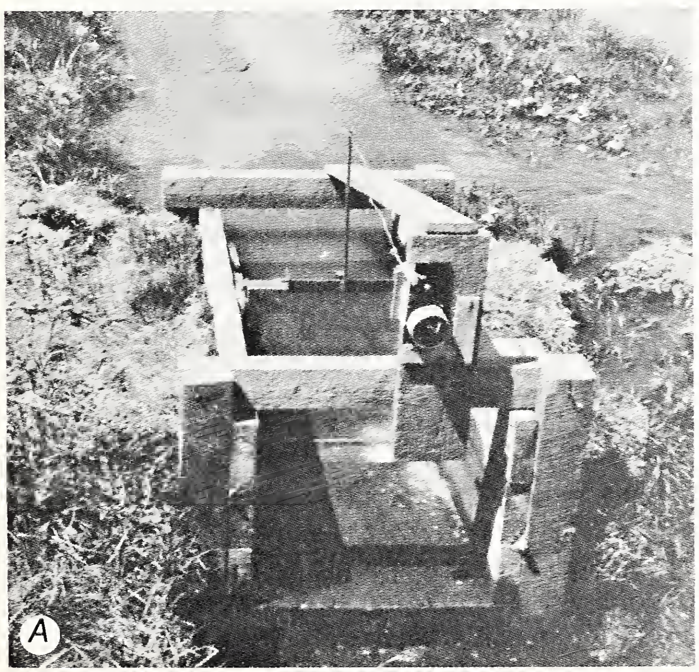
matic gates might require the irrigator to visit the structures once each day. Assuming that 6-hr irrigation sets are required, the irrigator can adjust four gates and set the times so as to give four changes of water during the next 24-hr period. One day later, the irrigator sets up the next four structures for that day's operation. Semiautomatic structures may also be useful for making one or two irrigation set changes during nighttime hours or during midday (for part-time farmers).

Semiautomatic structures include a wide variety of simple gates and release mechanisms, often capable of being fabricated in farm shops. For example, figure 22 illustrates a simple drop-open gate installed on mountain meadows at the CSU Mountain Meadow Research Center, near Gunnison. The wooden check structures were already in place in this ditch and were used with flashboards to check water and flood-irrigated meadows. In the structure pictured, a simple sheet metal panel was substituted for the flashboards. This panel bears against a cleat at the bottom of the channel; the lever arrangement at the top holds the panel firmly against angle iron seats when the gate is closed. At the end of the interval dialed on the spring-wound timer, the series of levers are released and water pressure pushes the gate open, allowing the stream to advance to the next check in the system.

Drop-closed structures generally involve a solid gate made of sheet metal, plywood, or other rigid material, hinged at the top and opening to the upstream side of the check bulkhead. These structures are generally simpler to construct than drop-open checks because the force of water against the closed gate-leaf tends to push it tightly against the seat and helps maintain a waterproof seal.

The choice of drop-open and drop-closed gates for a project is often based on the irrigator's preference. With drop-open checks, irrigation proceeds from the upstream end of the field ditch. With drop-closed gates, irrigation starts at the downstream end of the ditch and proceeds upstream. The two systems have markedly different characteristics in case a gate fails to function properly and different fail-safe arrangements are required. A limited number of clock-operated check structures are currently in use in Colorado, Wyoming, Idaho, and Montana, some of which have been developed and manufactured by farmers.

Where hydraulic or pneumatic controls are used to automate ditch turnouts, drop-open or drop-closed systems may be used to control check structures in the ditch. Figure 23 illustrates a drop-open check, constructed of steel panels, and a flexible butyl rubber gate, which is opened by a pneumatic cylinder on the same control system as the pipe turnouts in the



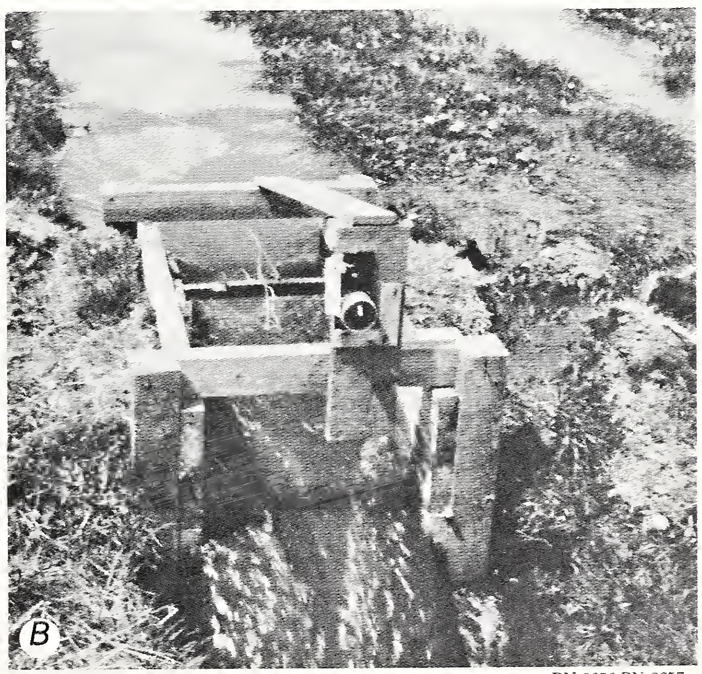


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FIGURE 22. — Simple drop-open gate, *(A)* developed by A. S. Humphreys *(33)*, being field tested in mountain meadow at Gunnison, Colo. The 24-hr timer allows preset time needed for diversion of stream. *(B)* Moment of release as clock releases wire that holds latch at top of gate.

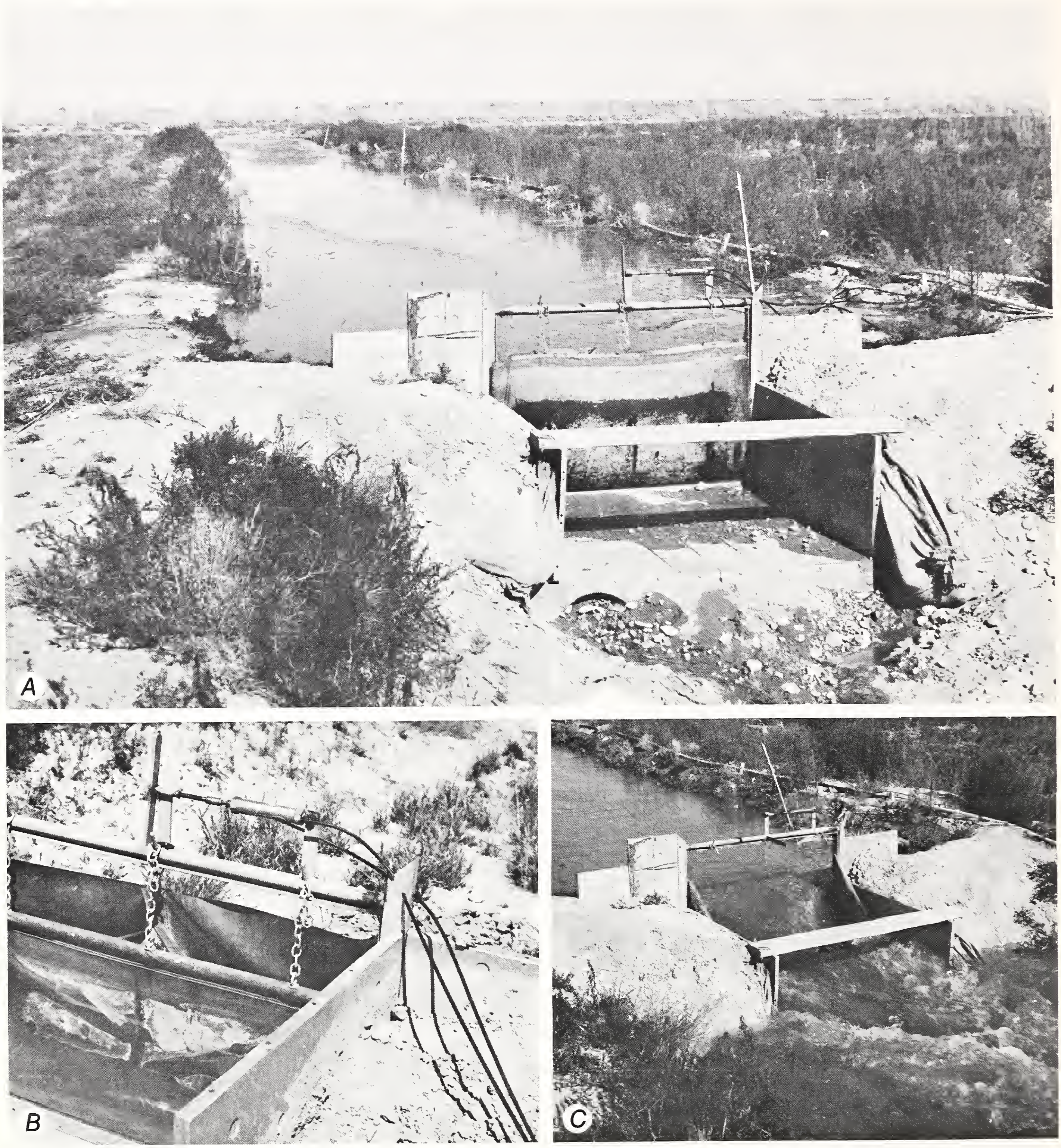

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FIGURE 23. — Pneumatically operated drop-open gate *(A)* constructed of butyl rubber sheeting and steel panels in a field lateral on the Seedskadee development farm, Fontenelle, Wyo. This gate controls streams of 7 to 8 ft^3/s. It was used in conjunction with pneumatically opened and closed turnouts to irrigate graded borders. At the same time the gates downstream of the check open, the cylinder *(B)* at the check retracts (see inset), allowing water pressure to force the check open *(C)* and fill the next reach of the lateral.

ditch. The mode of operation of this check is self-evident. Manual resetting between irrigations is required.

A somewhat different type of cylinder drop-open check (fig. 24) was installed in a small lined channel on the Imperial Valley Conservation Research Center, Brawley, Calif. In this case, the cylinder is operated by hydraulic pressure; general function of the check and turnout system is identical to that described in figure 23.

Tip-Down Checks

A gate similar in many respects to the hydraulic cylinder drop-closed gates is the tip-down check shown in figure 24*C*. This gate was used in a lined channel at the CSU Mountain Meadow Research Center near Gunnison. The push-off pipe turnout valve was described previously (see "Ditches with Pipe Turnouts, Outlet Control"). The tip-down check is shaped to seat in a trapezoidal concrete-lined ditch. The gate is pivoted at the top and counterweighted to maintain its normally open position. Operation logic is as follows: Irrigation commences at the downstream end of the lined channel and proceeds upstream. The rod from the plastic hydraulic cylinder at the top center of the check extends at the same time as do rods from the hidden cylinders on the push-off gates in the turnouts. Thus, the tip-down check is forced into the flowing stream of water, which tends to complete the closure and aids in maintaining a waterproof seal. At the end of the ir-

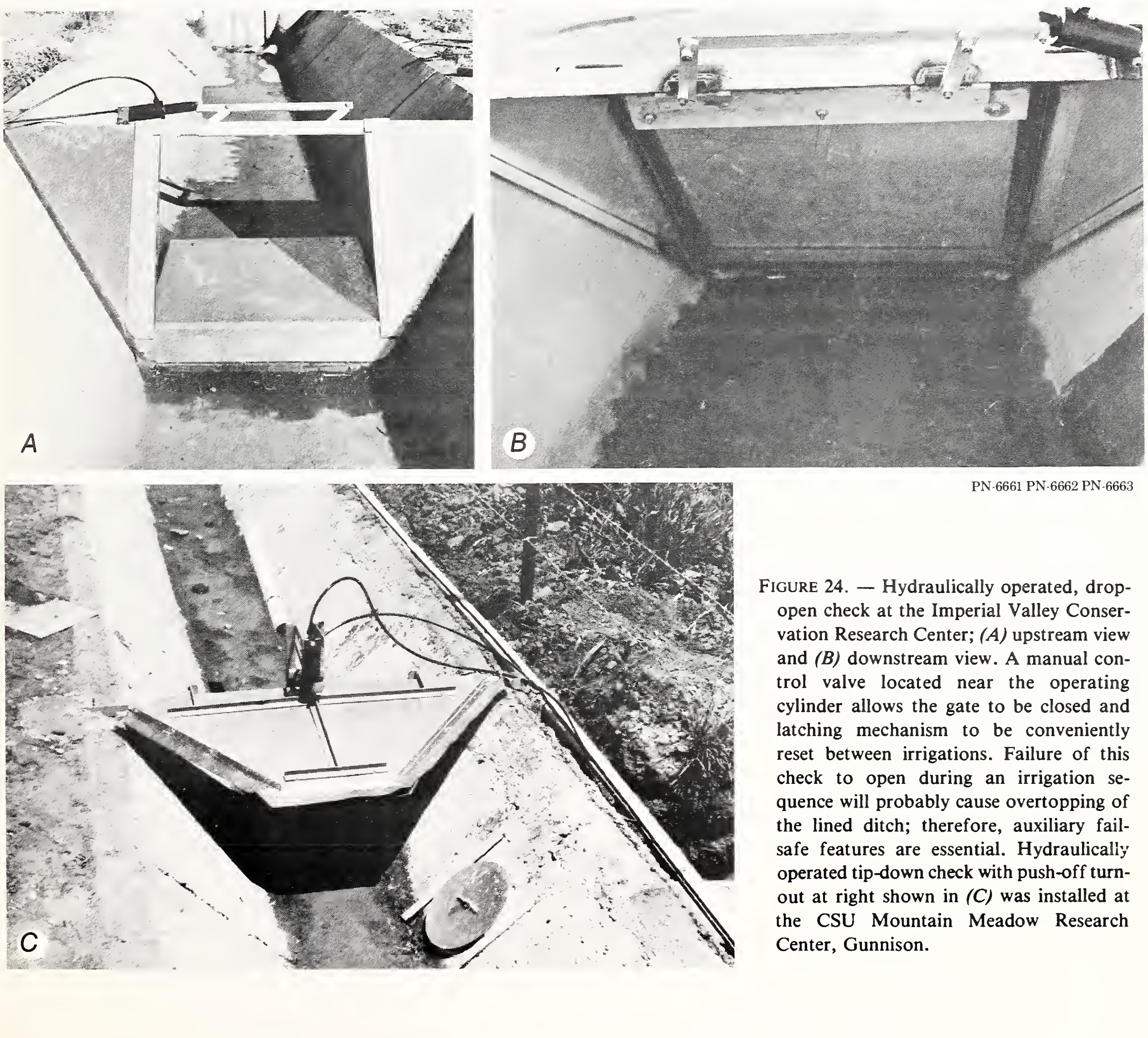

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FIGURE 24. — Hydraulically operated, drop-open check at the Imperial Valley Conservation Research Center; *(A)* upstream view and *(B)* downstream view. A manual control valve located near the operating cylinder allows the gate to be closed and latching mechanism to be conveniently reset between irrigations. Failure of this check to open during an irrigation sequence will probably cause overtopping of the lined ditch; therefore, auxiliary fail-safe features are essential. Hydraulically operated tip-down check with push-off turnout at right shown in *(C)* was installed at the CSU Mountain Meadow Research Center, Gunnison.

rigation interval, all cylinders retract and the turnouts are closed. At the same time, the next set of upstream turnouts opens and that check closes. Water pressure on the downstream check is thus relieved, and the check is automatically reset.

Modulating Gates

Automatic modulating gates were first constructed to replace the steel slide-gates that were being hand operated to irrigate "level-level" irrigation systems in Hawaii *(30)*.

A model of a modulating gate, incorporating the steel slide gate, a hydraulic cylinder, and a four-way valve (fig. 25), was built and successfully tested in the CSU Hydraulic Laboratory. The model maintained a constant head in a simulated level ditch, using stilling wells and floats to activate the four-way hydraulic valve (see appendix fig. 4). Hydraulic cylinders with O-ring seals tend to be damaged by sand grains in water, so the pressurized water supply to activate the cylinders must be filtered.

Numerous gates were developed and field tested on "level-level" irrigation systems in Hawaii (fig. 26). Center-pivoted gates required smaller actuating forces than gates hinged at the edges. Some were pivoted horizontally; others, vertically *(30)*. A number of hydraulic cylinders were tried beginning with brass, then plastic (PVC), and finally two Toro Manufacturing Co. plastic pistons in tandem to swing a vertically pivoted steel gate. None of these attempts was very successful. The main problems were associated with long, pressurized water lines, lack of electric power in remote areas to pressurize water, and the relatively high cost of hardware and installation. All components of this system had to withstand the burning or "firing" of the canefields, or had to be portable enough so that most components of system could be removed when firing took place.

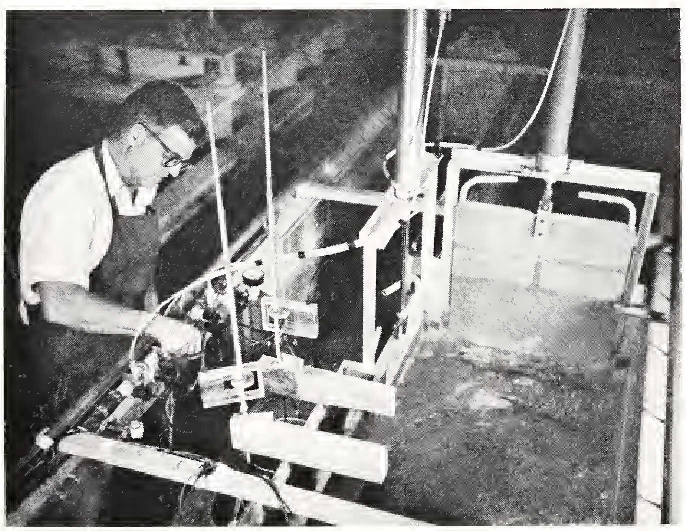

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FIGURE 25. — Senior author adjusts four-way hydraulic valve used to modulate steel slide gates to maintain constant head in level distribution lateral for irrigating furrows. Note that brass and plastic cylinders also are being tested for reliability.

One other factor that retarded further development of hydraulic automation systems in Hawaii was the concurrent interest in low-cost, clock-operated, drop-open and drop-closed check gates. Humphreys and Bondurant *(39)* performed much research and development on these gates that ultimately were used on some Hawaiian sugar plantations. Sugar plantation research and development personnel made rapid strides in developing a variety of semiautomated checks; however, even these noteworthy developments, as promising as they appeared to be, have since yielded to mass production and installation of drip irrigation systems that can economically be burned and replaced every 2 years. Hawaiian Commercial and Sugar Plantation on Maui now has 5,000 acres under drip irrigation.

Another version of an automatic check gate was used at Yuma in conjunction with automated pipe turnouts for irrigation of citrus. Here, transfer of water from one irrigated block to another required a check that could be remotely operated in sequence with the pipe turnouts *(27)*. Several designs were investigated. One consisted of a pivot check where the opening and closing force again was provided with a hydraulic cylinder (fig. 27*A*). This check was never very satisfactory because of leaks resulting from inherent flaws in its construction and the corrosive action of salts in water used to operate the hydraulic cylinder.

Semiautomatic Checks

Another check at Yuma was semiautomatic since it had no automatic reset capability (fig. 27*B*). A latching mechanism was placed on both sides of the gate frame near the bottom. When released with a Toro piston, upon signal from an

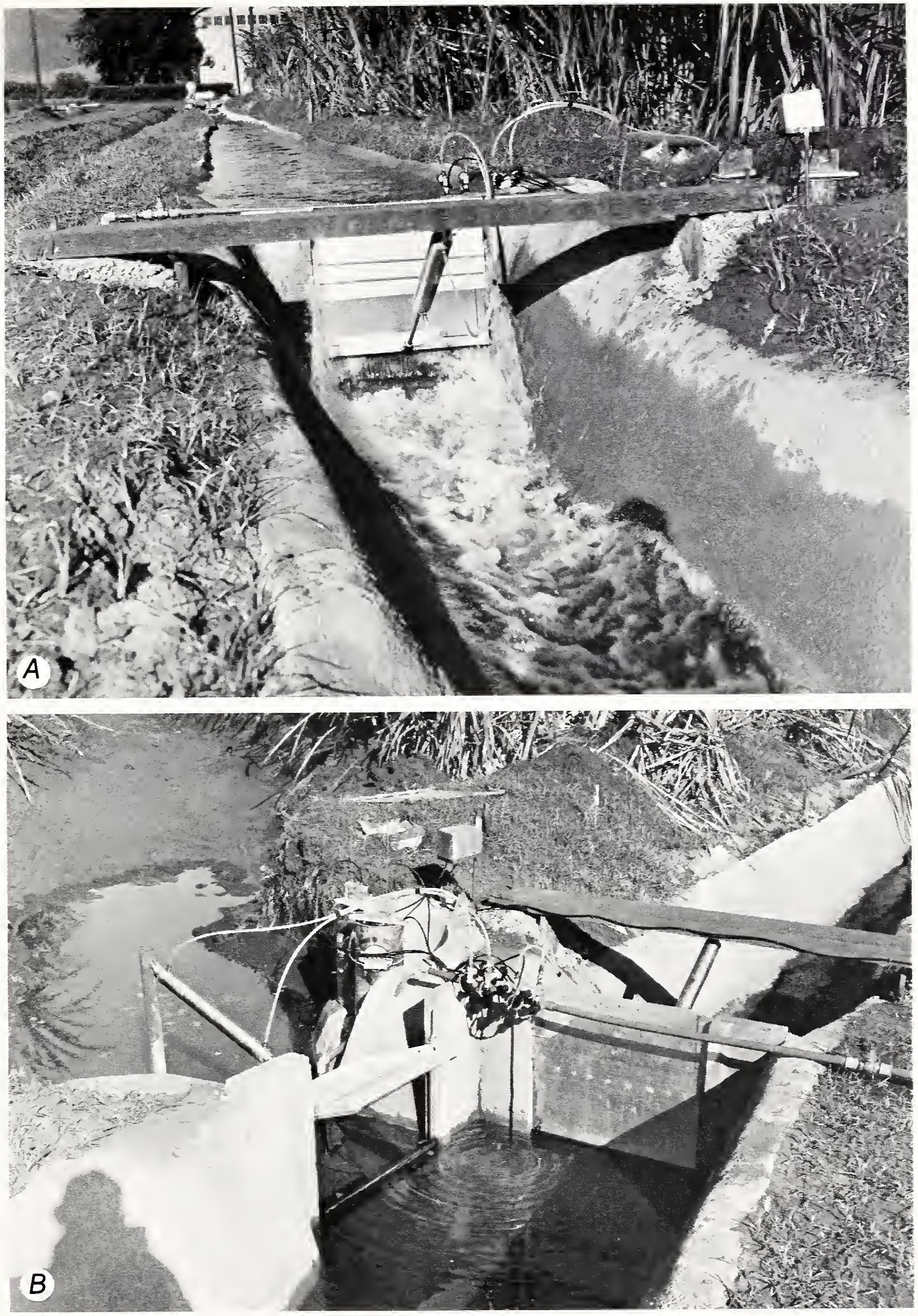

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FIGURE 26. — Field installation of horizontally pivoted modulating gate on "level-level" irrigation system located on the Hawaiian Commercial and Sugar Plantation, Maui, Hawaii, 1968. Note water in *(A)* is being automatically bypassed to downstream level supply ditch while system maintains constant level of water diverted into level ditch at right. In *(B)*, gates are in automatic mode to check and divert entire flow of water into level supply ditch at left until preset depth has been attained.

electromechanical controller, water pressure behind the gate forced it to open where it "rode" on top of the flowing water (fig. 27*C*). The semiautomatic gate(s) had to be manually locked in position at the beginning of each irrigation before starting the timer. This is not altogether bad, since it forced the grower to examine the system periodically for possible maintenance needs. This gate can be manually closed with flowing water in the ditch (fig. 27*D*),

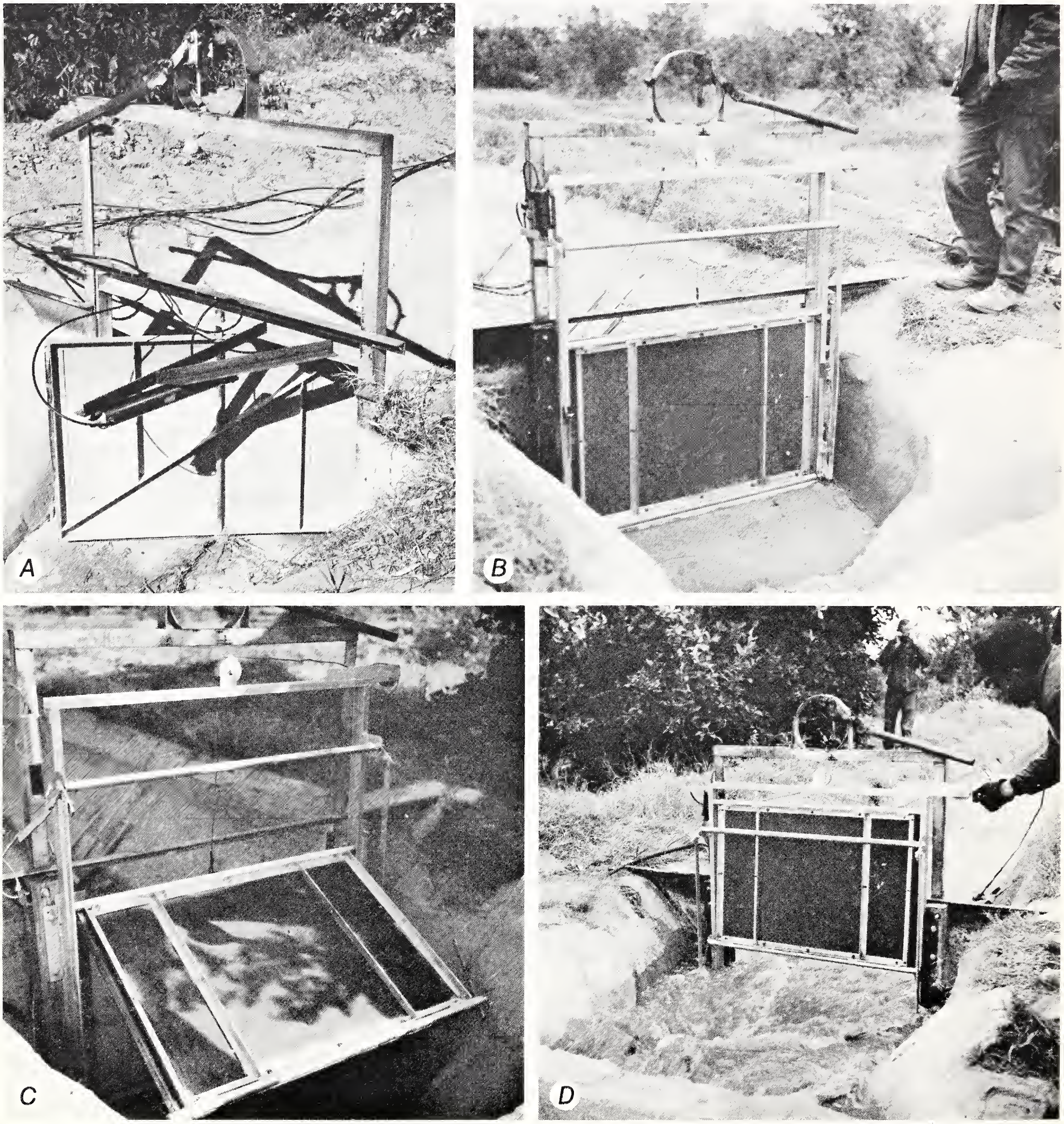

FIGURE 27. — Experimental pivot control gate *(A)* in farm lateral on Yuma Mesa, Ariz., replaced jack-gate for checking water. Horizontally pivoted gate *(B)* with no automatic reset capability. Note Toro cylinder at left, which releases gate at bottom to assume position shown in *(C)*. In *(D)*, gate is lifted during manual reset in flowing water.

a useful capability in case of malfunction in other sections of the system.

Like the Yuma automated system, the one at Blythe, Calif., on the Fisher Ranch, also used semiautomatic checks to augment or replace the standard jack-gate already in use. One possibility explored is shown in figure 28*A* and *B*. Note that the gate pivots at the bottom and locks at the top. The locking

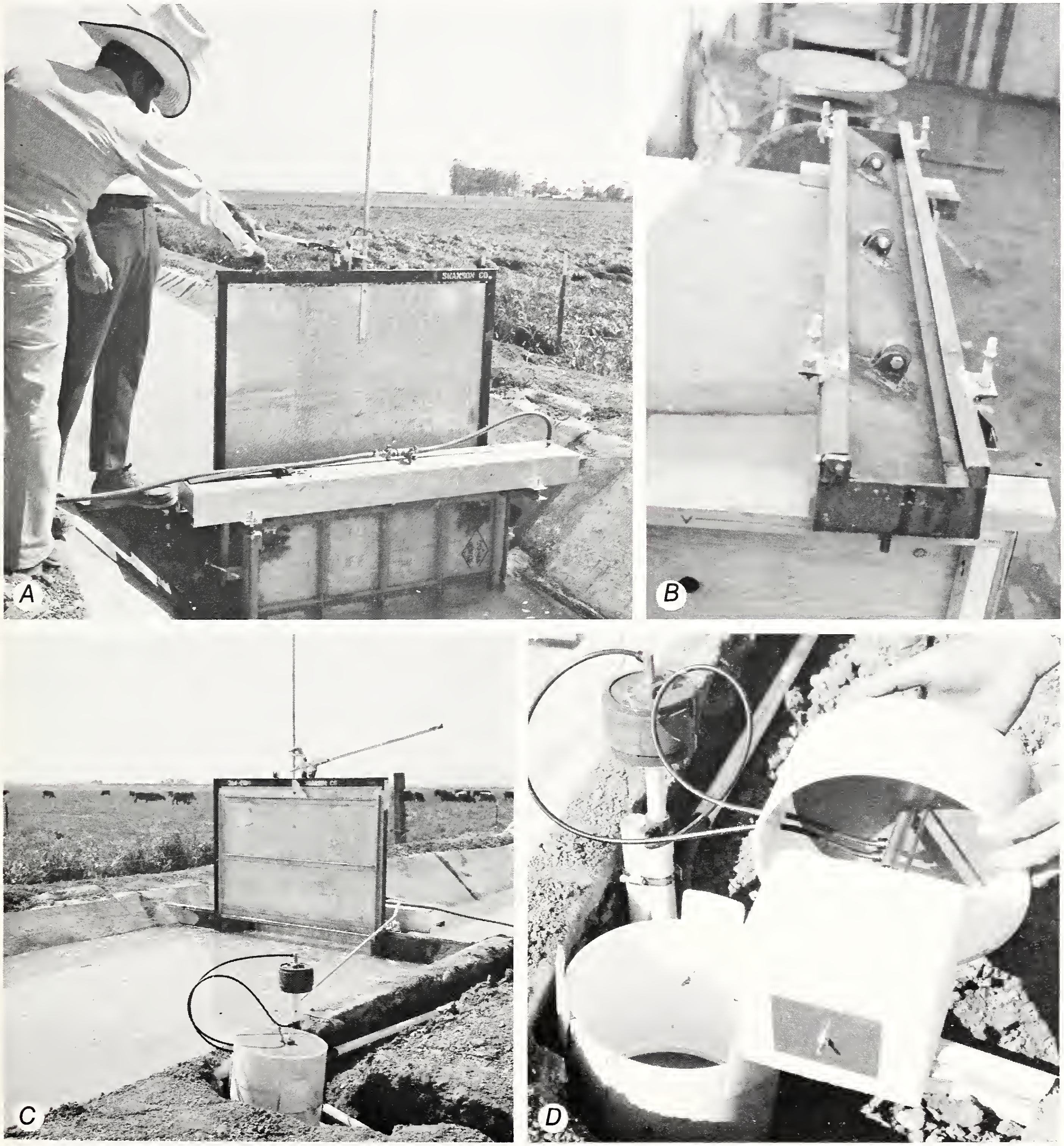

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FIGURE 28. — *(A)* Drop-open, pillow-operated check gate attached to downstream side of existing jack-gate in automated section of farm lateral on Fisher Ranch, Blythe, Calif. *(B)* Inverted bonnet with pillow and wheels that lock onto top of gate when pillow is pressurized. *(C)* Fail-safe float valve designed to open turnouts rapidly in case water overtops farm lateral due to malfunction of system. *(D)* Internal view of styrofoam float and three-way spool valve.

mechanism consists of a "bonnet" in which a rectangular pneumatic pillow is placed. The pillow is made from 4-inch butyl rubber pipe and is compatible with air line operating pressures (5 psi) used to inflate the pipe turnout pillow previously discussed. When inflated, a hinged plate with catch wheels is forced down on top of the gate frame (see inset, fig. 28*B*). Upon release of air pressure, the water behind the gate forces the catch wheels and hinged mounting plate upward, allowing the gate to drop open. A water-filled depression in the concrete channel floor cushions the impact of the falling gate. As pictured in figure 28*C*, the pillow check is attached to an existing jack-gate that can be used for manual override of the automated system. Pillow controlled gates are synchronized to release water to the next bay only when downstream turnouts are open for the next irrigation set. This mode of operation prevents overtopping of the downstream channel section. The fail-safe feature (figs. 28*C* and 28*D*) opens all outlets in one set if water begins to overtop the ditchbank.

Jack-Gate Turnouts

In large irrigation channels, commercially available jack-gates are commonly used to check water. The slide gates are hand-operated by means of a permanently installed jack mounted on the gate frame. Where large irrigation flow rates (10 to 35 ft^3/s) are available, these jack-gates are also installed in the side of the ditch to serve as field turnouts. A single turnout into a 5- to 40-acre field is commonly used in areas of the desert southwest where level basin irrigation is gaining in popularity.

The first automation for such jack-gates was developed by Payne and Duke[6] at Fort Collins and was installed on the Fisher Ranch in Blythe in the spring of 1975. The actuator for the original jack-gate system was a shop-made pneumatic cylinder, with 5-inch bore and 36-inch stroke. The cylinders were made from drawn-over-a-mandrel (DOM) steel tubing with O-ring endcap seals and were held together with external drawbolts. The jack-gates were modified in the field by replacing the angle iron headframe with 4-inch channel to provide support for the cylinder. The manual jack was moved to one side and reinstalled as a manually operated backup system (fig. 29).

As a fail-safe feature to protect the ditch in case air pressure was lost, the jack-gates were fitted with garage door springs attached to the headframe and bottom of the gate leaf (fig. 29*A*). Float-actuated dump valves were installed to sense critically high water levels in the ditch. When the dump valves were actuated by high water, the gate cylinder was disconnected from the pressure source and the springs opened the gate, releasing water from the ditch.

The cylinders were controlled by a four-way spool valve, used to direct air pressure (about 60 psi) from a common ¾-inch air line to either the top or bottom of the cylinder for two-way operation (appendix fig. 6). As initially installed, the spool valves were pilot operated with individual ¼-inch O.D. polyethylene tubing running to the control station. The spool valves were later moved to the control station.

The original system at Blythe consisted of 12 turnouts and 2 ditch checks, covering one-third of a mile of ditch and irrigating 193 acres (fig. 29*C*).

Because of the large flow rates diverted through each turnout (up to 36 ft^3/s), special measures were required to prevent soil erosion. Energy dissipation structures were modeled in the laboratory at Fort Collins to develop the final design. The final structure (fig. 30), 36 ft long, utilized a baffle board in front of the gate opening, dissipation blocks in the dissipator itself, an overflow sill set above field grade, and an apron (0.3 ft below grade as recommended by L. J. Erie, oral communication) to obtain uniform flow distribution and dissipate energy through a hydraulic jump induced over the apron. Figure 30*B* shows the energy dissipation structure in operation with an estimated flow rate of 55 ft^3/s. Even where the soil was freshly disturbed by leveling, erosion was controlled satisfactorily. These structures, however, were ineffective when the baffle boards were removed or improperly installed and when soil deposited by tillage equipment was not removed.

Having assisted us with installation of the Blythe system, L. J. Erie and A. R. Dedrick made further improvements in the turnout control system and installed several systems in the Wellton-Mohawk Irrigation and Drainage District in Arizona. They located suitable commercially available pistons, fitted the fail-safe spring inside the piston, and designed less expensive energy dissipators for the smaller irrigation flows of the Wellton-Mohawk project in Arizona *(6, 16, 59)*.

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[6] Payne, M. L., Duke, H. R., and Haise, H. R. Further developments in automation of level basin irrigation. Oral presentation at winter meeting, American Society of Agricultural Engineers, Chicago, December 10-13, 1974.

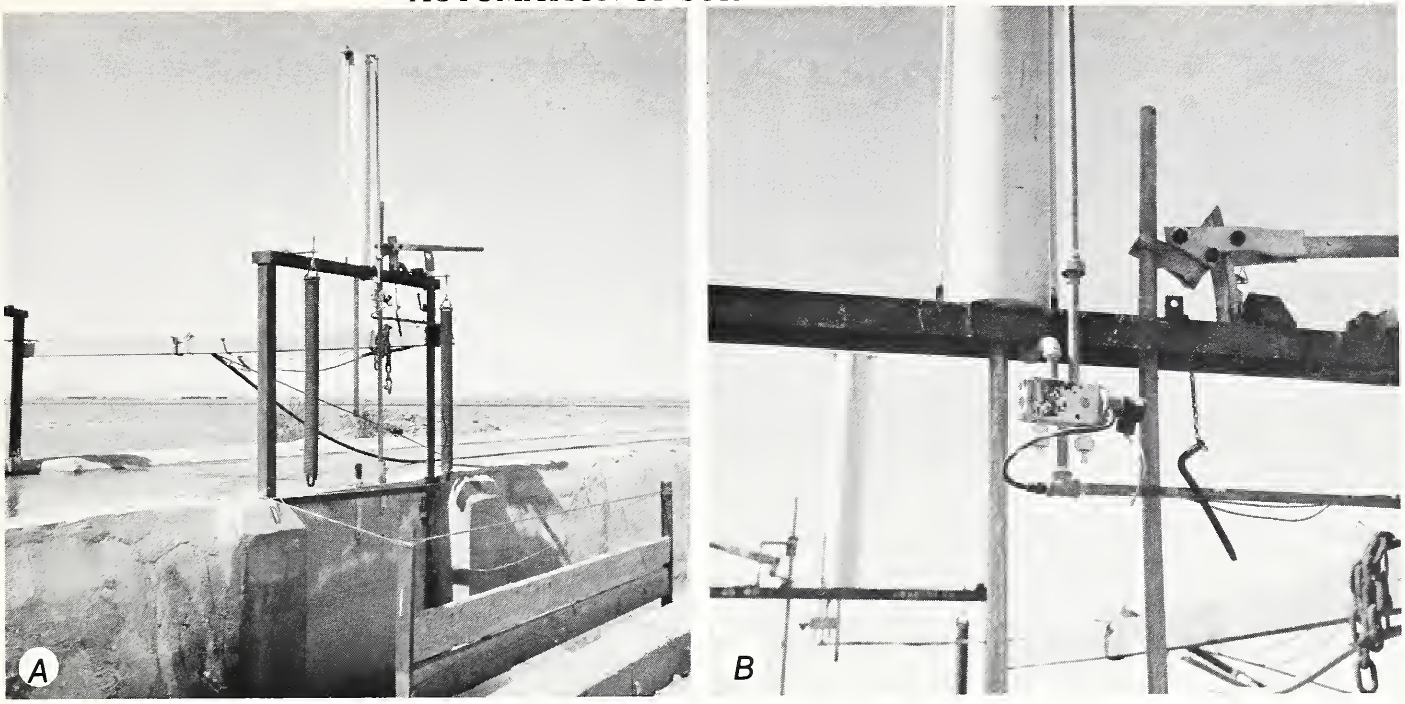

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FIGURE 29. — Original jack-gate turnout automation system *(A)* installed on Fisher Ranch, Blythe, Calif., showing *(B)* channel iron replacing original head-frame to provide mounting base for actuating cylinder. Manual jack rod was moved to one side to allow centering cylinder. Note four-way valve for directing air pressure to cylinder. Jack-gate *(A)* was installed in side of ditch when energy dissipator was constructed. Large springs open gates if control system fails. Twelve turn-outs were installed *(C)* on a ditch serving 193 acres.

GATED PIPE AND FLUMES

Attempts to automate gated pipe outlets, used principally for furrow irrigation, have been far less successful than automation of pipe turnouts and check-gates in water distribution ditches. The reasons for this will become apparent in the following discussion.

Slide Gates

Fischbach *(14, 20)* attempted to open and close commercial slide gates in standard gated pipe by using a connecting rod and hydraulic cylinder to provide the actuating force. He found that the connect-

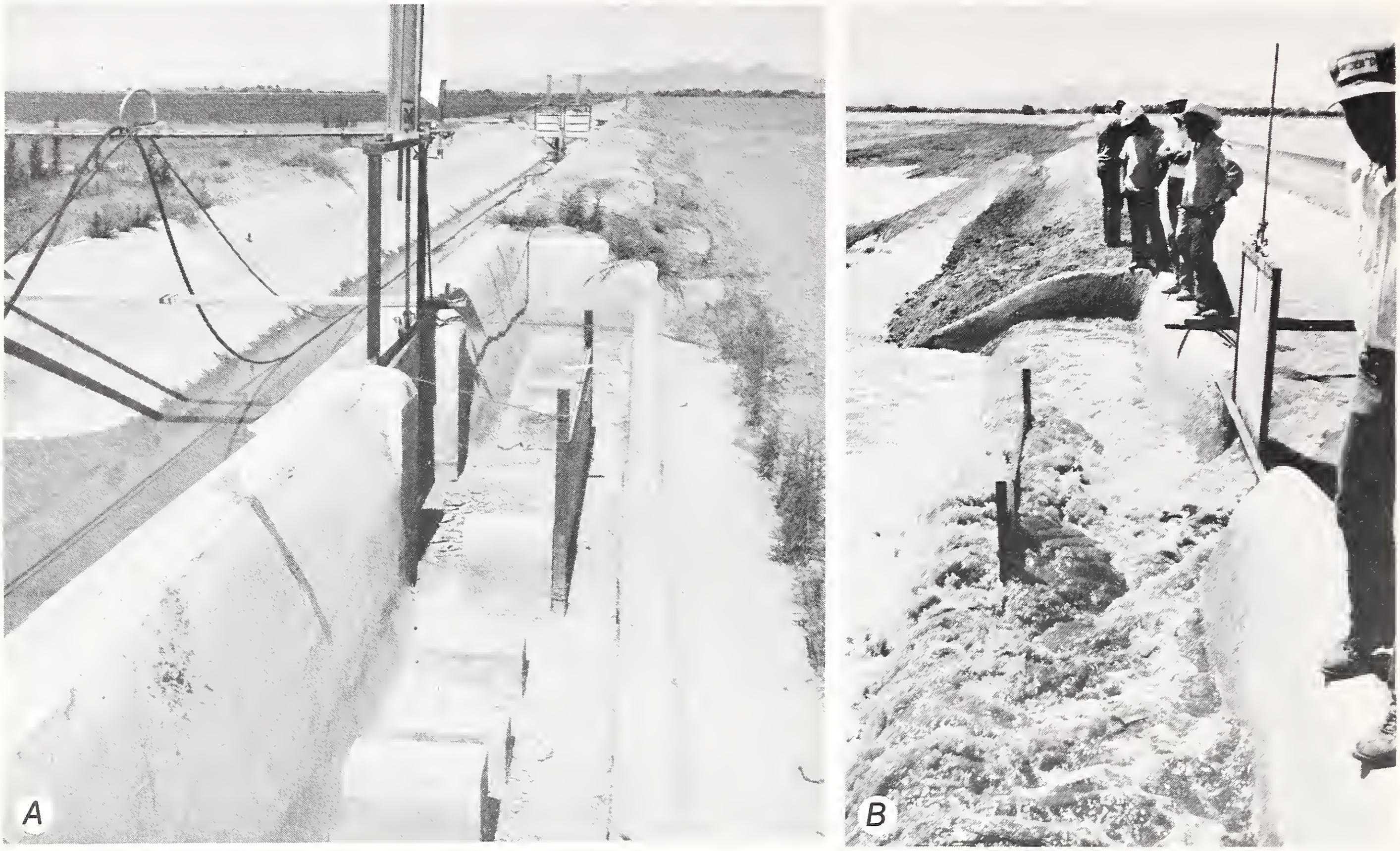

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FIGURE 30. — Energy dissipation structure designed for jack-gate turnout. Baffle and dissipator blocks *(A)* distribute water uniformly across structure. An estimated 55 ft³/s *(B)* were released into level basin with minimal erosion.

ing rod and gates would not move freely, in the field, because of expansion and contraction of pipe and connecting rod components with change in temperature. He concluded that each outlet should have an individual valve capable of remote control. The number of outlets tied together for a single irrigation set would depend upon water supply, soil, crop, and topographic conditions.

Modified Epp-Fly Gated Pipe Valve

Using Fischbach's work as a guide, we first tried to automate individual pipe turnouts using a standard Epp-fly gated pipe outlet (fig. 31*A* and *B*). The Epp-fly gate jam nut was used to attach the valve assembly and metal transition box into the wall of the 8-inch aluminum pipe. A miniature pneumatic pillow at the top of the box provided a closure on the valve seat. Figure 31*C* to *I* shows a similar automatic system that uses a pneumatic pillow to control waterflow in a hydrant. Standard pipe gates are then mounted in the hydrant. Several methods of distributing irrigation streams from hydrants to furrows are illustrated in figure 31*D, E, F,* and *G.*

Payne Gated Pipe Valve

Another valve developed by M. L. Payne and manufactured commercially by the Toro Manufacturing Co. in limited quantities is shown in figure 32*A* and *B*. A commercial market for automated gated pipe valves seemed to exist, not only for thousands of feet of gated pipe already in use on irrigated farms on the U.S. mainland, but also for possible conversion of so-called Wailua flumes to automated irrigation systems on some sugar plantations in Hawaii.

The Payne valve, like the Epp-fly, can be locked into a hole in the wall of aluminum pipe (8-inch diameter) by using a jam nut and specially designed rubber gasket. The valve opens on the inside of the irrigation pipe. Water pressure connections to the miniature hydraulic cylinder were originally located inside the pipe to allow internal manifold connections for the number of valves in an irrigation set.

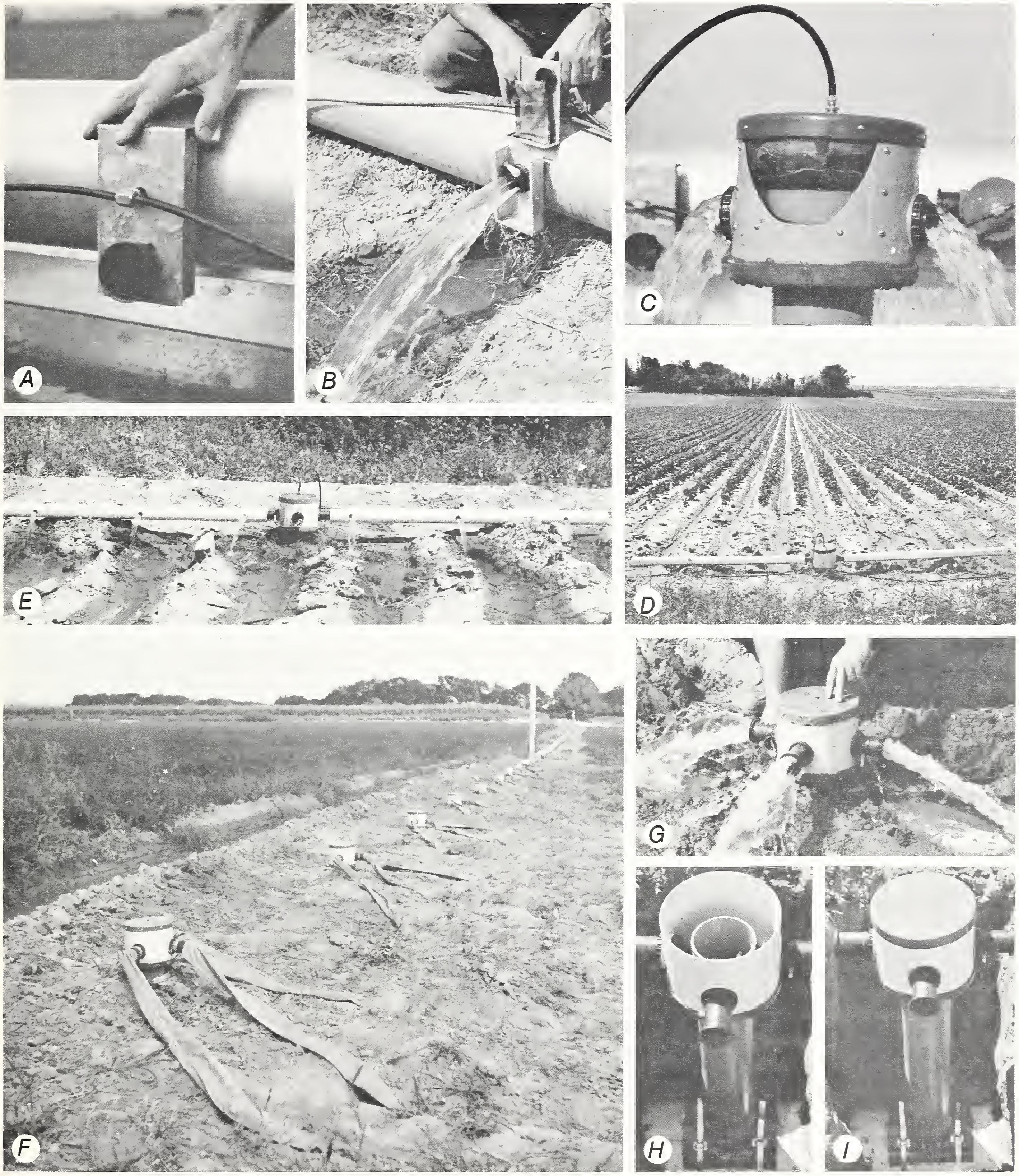

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FIGURE 31. — *(A)* Modified Epp-fly valve installed in metal transition box on 8-inch aluminum pipe, and *(B)* inside view of valve showing pillow, flowing water, and valve lever to adjust discharge. Other schemes to utilize pillow-disk valve with hydrants for furrow irrigation include: *(C)* pillow-disk valve mounted in riser with Epp-fly valves to control discharge; *(D, E)* use of PVC pipe with holes to distribute water to furrow; *(F)* is same as *(C)* but with long "socks" to channel water to furrows and prevent erosion; *(G)* discharge from Epp-fly gates without socks; *(H)* riser with top removed showing valve seat and Epp-fly valves in hydrant wall; and *(I)* same as *(H)* with top of hydrant in place.

External quick couplers and jumper tubes placed at the ends of each pipe section were used to connect several pipe sections together as needed.

We also tried installing the valve in a flexible butyl rubber pipe with all control lines inside (fig. 32*C* and *D*). The flexible pipe with valves was difficult to handle, communication lines interfered with operation when they fell between the valve leaves and seats when the valves closed, and the flexible pipe was difficult to position since it tended to roll until the valves were pointed nearly downward.

Other basic weaknesses in the Payne pipe valve were as follows: (1) It was normally closed and thus had no fail-safe capability. (2) flow rates through valves nearest the water source were less than at far end of irrigated set, (3) all valves did not close tightly,

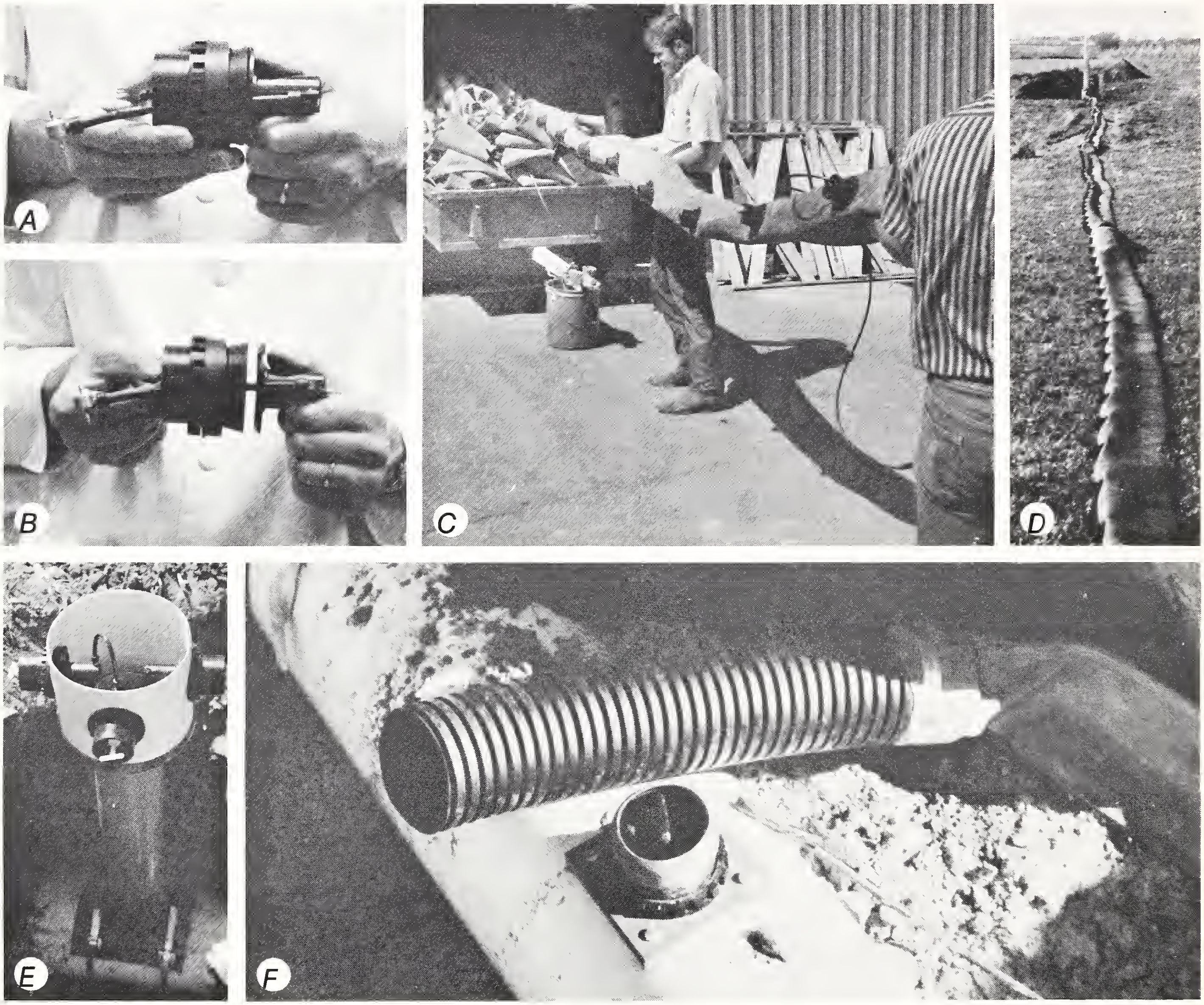

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FIGURE 32. — Normally closed commercial gated pipe valve *(A)* in closed position and *(B)* in open position. Valve opens inside aluminum pipeline. Brass tee and plastic tube connected to piston permit external manifolding of pipe valves. Originally, connections between valves were made directly to piston inside irrigation pipe. *(C)* The Payne gated pipe valve inserted in flexible butyl rubber tubing and *(D)* installed in field for testing. All ¼-inch polyethylene tubes used as manifolds are inside flexible rubber pipe. *(E)* Plastic riser and hydrants, with lid removed for viewing, utilizes three Payne gated pipe valves. Water is controlled with Payne valves, each of which can be adjusted to produce the desired flow rate. Control tubing for the valves is protected from damage by locating it within the plastic pipe system. *(F)* Payne valve is installed in buried PVC pipe. Flexible riser and "duck-bill" — a shaped valve of collapsed rubber tubing (right) — are attached to Payne valve before trench is backfilled. When valve opens, pressurized water erodes a channel to soil surface without too much shovel work.

and (4) lateral drag forces of flowing water on valve cylinders caused distortion of seals and loss of operating pressure. The problem of trash collection on lines installed internally was later avoided by modifying the valve to permit hookup to manifolds outside the pipe (fig. 32*A* and *B*).

Other possible applications of the Payne valve were explored. Figure 32*E* and *F* show valves mounted in a miniature hydrant made from PVC pipe. Hydrant risers were solvent welded to a buried PVC pipeline at desired spacings. One-quarter-inch polyethylene tubes were placed inside the buried pipe to provide air pressure to valves mounted in the riser hydrants.

Figure 32*F* shows the Payne valve installed on a PVC buried pipeline with a flexible polyethylene riser and duck-bill outlet for conveying water to the soil surface. When the valve was opened, water pressure forced the duck-bill to open and erode a path to the soil surface. It was self-closing when flow ceased. Some shovel work was needed to assist channeling of water from those valves that opened last. A probe could be inserted through the duck-bill and riser to manually adjust valve opening and discharge. One theoretical advantage of this system is that cultivation and plowing operations presumably could be performed over the pipeline without damage to the system. Worstell *(63)* and Varlev *(61)* have since developed other methods of supplying water to individual furrows from buried pipe laterals.

Scoop Gate (for Wailua Flume)

The Wailua flume is a channel used in Hawaii for conveying and distributing water to contour irrigation furrows. The flume is assembled on the soil surface in the field by joining short lengths of precast concrete channel sections. The flume derives its name from the sugar plantation in Hawaii where it was developed. The steep slopes of the Wailua installations frequently cause supercritical flow velocities in the flumes. Use of the Payne valve in the metal slide outlet gates of a model Wailua flume was unsuccessful because of the supercritical flow in the flume. We found that water velocities were too high to be turned at right angles into and through an opened valve at the rates necessary.

As a result, a special scoop-gate was designed for each outlet (figs. 33 and 34). The scoop gate was more satisfactory, but hardware was much too complicated. Because of supercritical flows in often steeply sloping concrete flumes, an effective gate must incorporate a scoop to intercept the stream of water and divert a part of it through the gate opening. Conventional operation of these flumes involves positioning of a manually operated gate. The gate shown in figure 33 is pivoted by remote cable control about a vertical axis.

Four scoops were tied together with spring-loaded wire that held the outlets closed. A plastic hydraulic piston installed at the opposite end of this wire kept it taut. When the piston was activated, the scoops in one irrigation set were pulled to a preset opening. Adjustment in the opening could be made individually on each scoop to achieve the desired discharge. No field tests were made of the system because of its complexity and because other developments at the time appeared to have more potential.

In one such system, called the piggy-back, one flume was mounted on top of the other. Trapdoors in the top flume diverted flow downward into a pipelike lower flume with outlets for each irrigated furrow. Trapdoors were spaced to accommodate an irrigation set and could be operated by the Toro differential area piston described under the section on "Butterfly Valve." When activated, the trapdoor closed, and water was conveyed in the top flume to the next downslope open trap door or point of diversion. An existing piggy-back flume was evaluated for such automation, but cylinders were never installed.

Pillow-Disk Valve for Gated Pipe

We previously described the pillow-disk valve adapted to a 16-inch standard pipe turnout to control discharge from an open ditch. The predecessor of that valve was the miniature (2-inch) valve described here. The exploded view (fig. 35*A*) and assembling steps (fig. 35*B* and *C*) show how the valve is constructed and inserted into aluminum pipe sections. Closure is accomplished by pressurizing the pneumatic pillow, which in turn applies force to the closing disk. The valve is closed when the disk is held firmly against the valve seat. The valve is normally open, thus loss of air pressure due to malfunction results in release of water from all valves in all sets.

The gated pipe valve first studied had a single discharge outlet, whereas the field version was modified to control discharge into two furrows. A sufficient number of these valves were fabricated to permit testing on a field scale (fig. 35*D, E,* and *F*).

In operation, a number of problems soon became apparent. Use of one closure to control discharge in two separate furrows did not provide regulation or

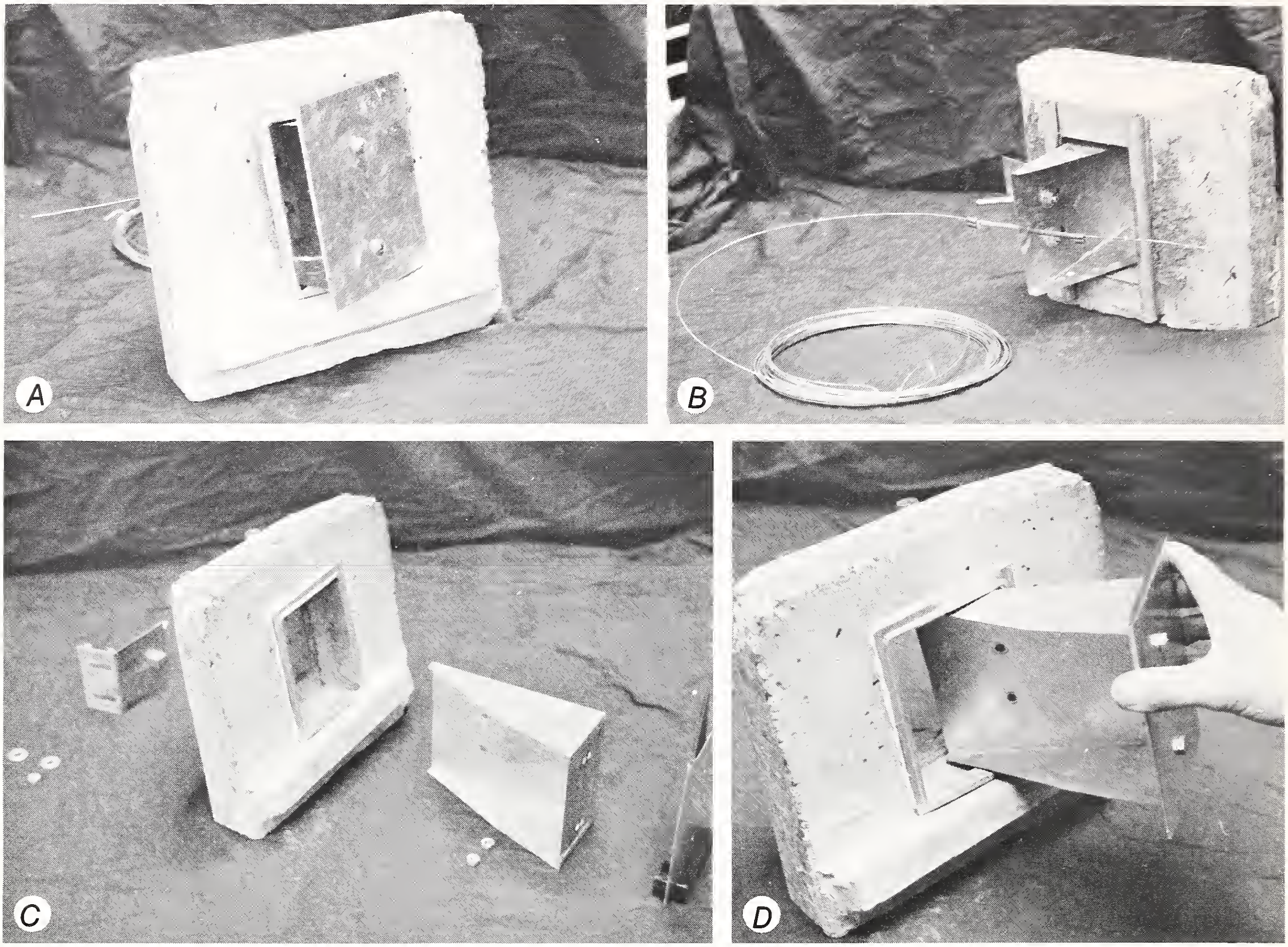

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FIGURE 33. — Model of scoop gate for Wailua flume. *(A)* Scoop mounted in concrete section of Wailua flume — view from inside flume; *(B)* view from outside flume, showing wire to pull series of gates open and closed; *(C)* gate components; *(D)* assembling scoop in flume.

adjustment of flow to compensate for variable furrow intake rates (that is, packed versus nonpacked furrows). Rotating the valve body in the irrigation pipe was only partially effective as a means of adjusting flow rates (fig. 35*C*). Inserting a manually operated butterfly valve in each outlet improved control of water application, but we were still plagued with other problems. For instance, it was very difficult to change size of set between irrigations if required by changes in soil intake capacity or irrigation water supply. Where pump-back or reuse systems are used, fixed set size may be used through the season.

Another problem was erosion in furrows at the point of discharge. We tried laying a polyethylene plastic film under the automated pipeline. Erosion was controlled, but directional control of the water to furrows was lost. Pieces of baled straw or hay also were used with greater success, but the wind moved some of these out of place between irrigations. Irrigation socks (fig. 36) are normally used to prevent excessive erosion at the pipe gate. Socks are subject to twisting and movement by wind between irrigations and have to be straightened prior to each irrigation. If each outlet along a long pipeline must be inspected prior to each irrigation, automation of the individual valve openings is of questionable value. In short, the erosion problem at the valve was never quite resolved.

Summary

Results of our work on automating surface pipe irrigation systems show that a single gated pipe valve can be used to control discharge to a single or double furrow. Problems of controlling twisting of irriga-

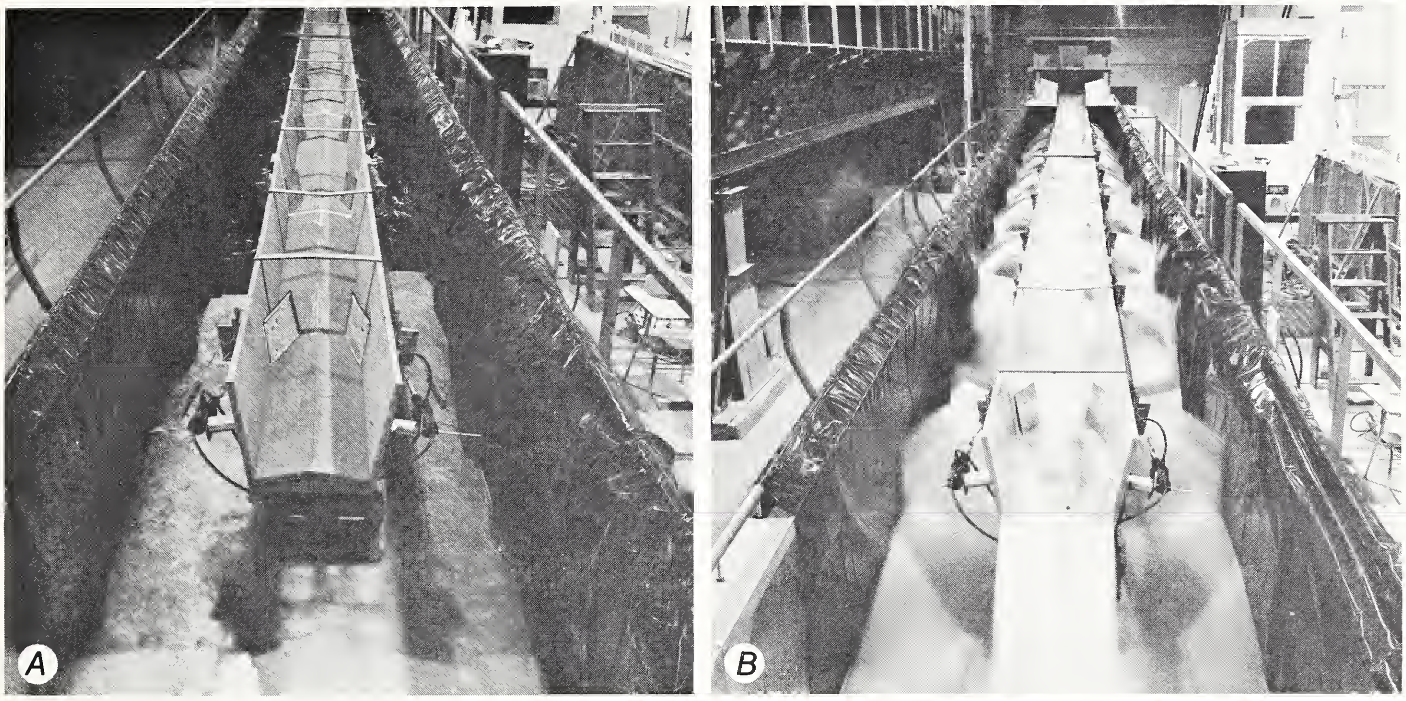

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FIGURE 34. — Laboratory model of Wailua flume and scoop gates: *(A)* A number of gates on one side of the flume can be attached to a cable and controlled by a single hydraulic cylinder at one end of the set. Each gate is individually adjustable on the cable. Spring tension allows some leeway in the precision of adjustment. *(B)* The time exposure shows streams of water being diverted simultaneously from all gates with a portion of the flow continuing on out the end of the flume.

tion socks by wind between irrigations, of changing size of irrigation set, and of compensating for variable furrow intake rates are yet to be resolved. Despite these drawbacks, however, further research and development are warranted to provide a simple, low-cost, normally open gated pipe valve that can be used to automate existing and new gated pipe systems. Automation of individual gates will be especially useful where portable gated pipe is connected directly to an irrigation pump and no part of the distribution system is buried. For buried pipelines equipped with risers, central control at the hydrant may eliminate the need for individual gated pipe closures.

CONTROLLERS AND COMMUNICATION

Tone Telemetry by Radio

In the early stage of development, we decided to explore the feasibility of using radio signals to activate battery-powered solenoid valves to control the USDA pneumatic O-ring on each alfalfa valve outlet. This system of control is schematically represented in Appendix figure 1. Basic components included a 12-channel transmitter, 12 receivers with a single designated tone for each, a 12-volt storage battery, a capacitor to activate a three-way solenoid valve, radio antennas for transmitter and receivers, and airtight quick coupler hookups between electric solenoid valves and alfalfa valve inflatable O-rings connected to a buried air supply line. To save development time, standard garage door remote opening circuitry was adapted to this application to verify and demonstrate the practicality of radio control in the field.

Several types of receivers were successfully tested, (fig. 37). Note that one had its own portable air supply capable of replacing buried air lines.

A number of disadvantages of radio control soon became apparent. Foremost of these was the need for standby power at the receiver and the excessive battery drain of the equipment used. Modern miniature circuitry can reduce the power requirement, but where electric valves and periodic capacitor recharge are required, power drain is still appreciable over a 5-

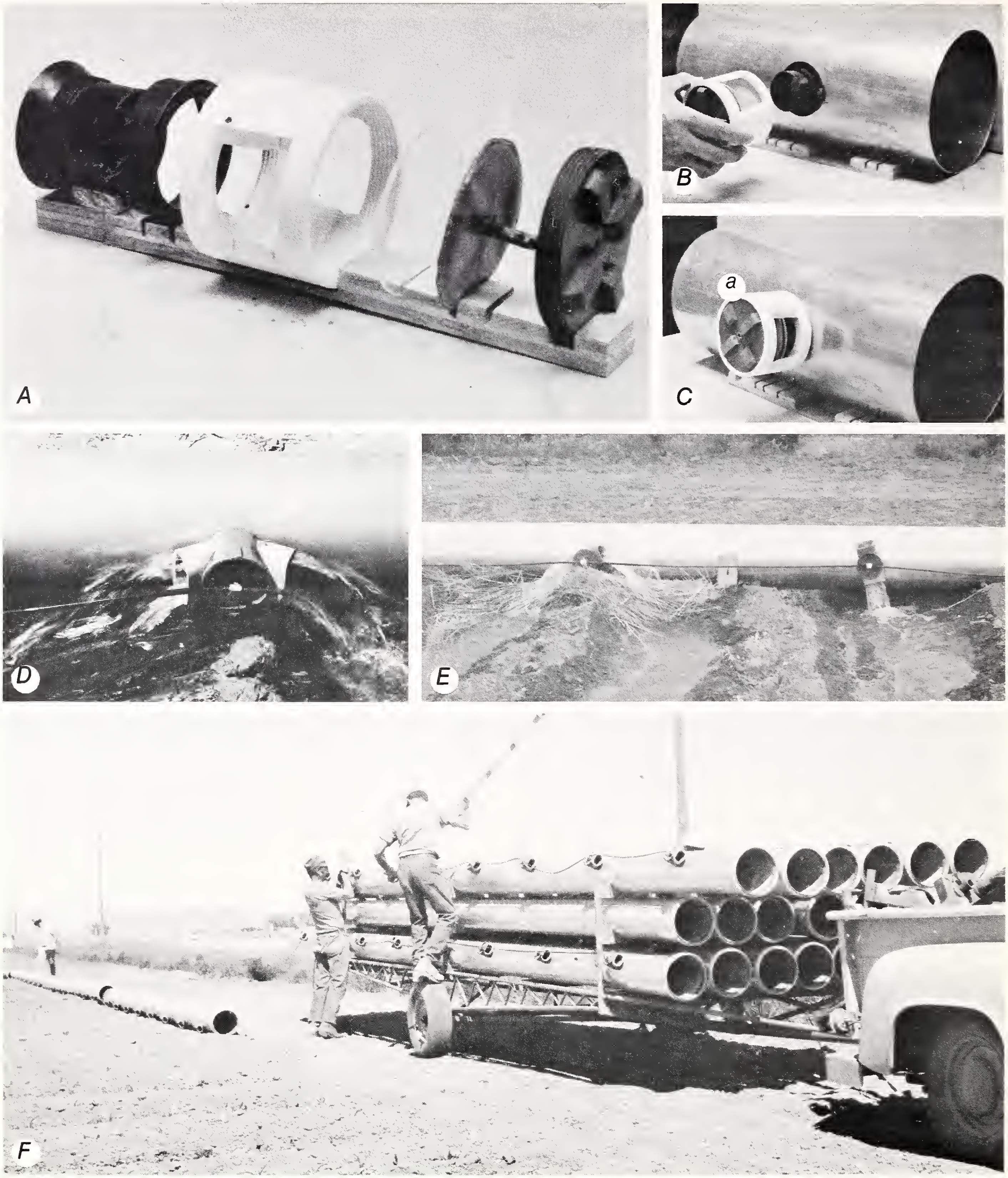

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FIGURE 35. — Pillow disk valve for individual pipe gate automation: Expanded view of the first version of this valve *(A)* shows the mechanism for attaching valve to gated pipe, *(B)* and threaded plate *(a)* in view *(C)*, which allows discharge regulation. Note that two holes in the valve body allow simultaneous irrigation of two furrows from a single valve. A later version of this valve *(D)* had molded spouts to better direct water to individual furrows. Note external air line for pillow inflation. Unequal division of the waterstreams flowing through this valve could be accomplished by tilting the valve body *(E)* where flow requirements of adjacent furrows differed or a valve served only one furrow. Gated pipe being assembled in field *(F)*.

or 6-day period. Another drawback of the original portable radio control instruments was the excessive weight. Again, substituting miniature circuits can overcome the weight problem. Reliability also was not good. Low battery power and spurious signals were continuing concerns. Modern electronics, utilizing digital encoding of receiver addresses, has eliminated the problems of spurious signals for such applications as garage door openers. This technique will undoubtedly be used in any further attempts at radio frequency irrigation control.

Tone Telemetry by Wire

Next we attempted to remotely control alfalfa valves with inflatable O-rings by using tone-telemetry and buried wires (fig. 38) instead of radio. The power source was standard 110 volts a.c. transformed to 24 to 36 volts d.c. Signals were transmitted by wire, us-

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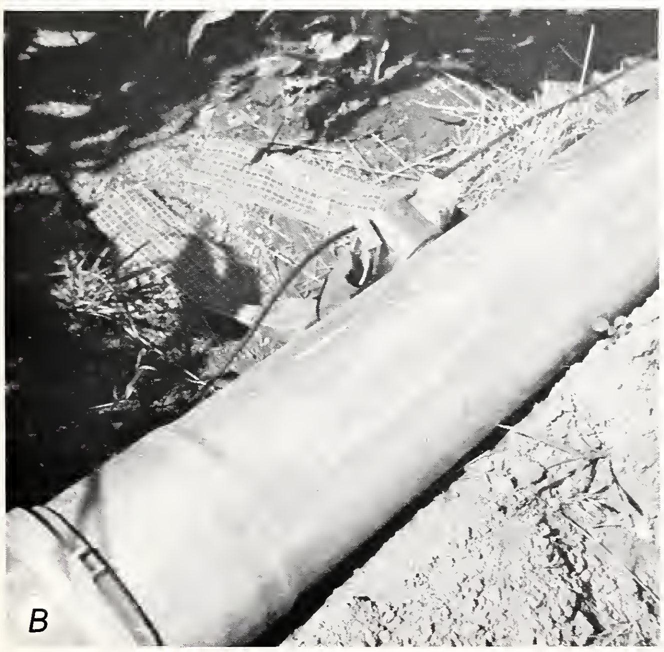
FIGURE 36. — *(A)* Field installation of automated gated pipe system near Waverly, Colo.; *(B)* latest version of pillow-disk gated pipe with slide gates to regulate flow at each outlet. Note sock *(B)* placed in single furrow to accommodate row spacing; and *(C)* with one valve set to irrigate two furrows.



ing three-strand, 16-gage insulated cable. To protect the cable, it was inserted in 1,000-ft lengths of ¾-inch polyethylene pipe by first threading the pipe with nylon cord attached to a "mouse" (lightweight piston that closely fitted the pipe bore) propelled by air pressure. The cord was then attached to the cable, which was then manually pulled into position. The wire and polyethylene pipe were buried to a depth of 20 inches for protection from tillage operations, using a modified tractor mounted ripper.

Airtight outlets for wire hookups to tone receivers and three-way solenoid air valves were provided at each alfalfa valve riser. The combined air line with wire was 3,200 ft long with control valves spaced 200 ft apart, the distance between risers. Although the solenoid-operated three-way valves were rated at 12 volts, as much as 32 volts were required to activate the valve at the far end of the line.

As was the case with the radio controls, the emphasis was on portability to reduce costs associated with solid-set systems. The transmitter had four channels or tones and four receivers to accommodate a 24-hour irrigation run (6 hr per set). In other words, each 12 or 18 hr the gated pipe, hydrant, and receiver equipment were to be moved to the next set to be irrigated. The farmer-operator found even this amount of labor to be unacceptable. Even though the initial cost is high, a solid-set system may be the only scheme acceptable to the farmer.

Once again, we were plagued by operational problems. Reliability was sacrificed by selection of poor electronic components and lack of quality control in

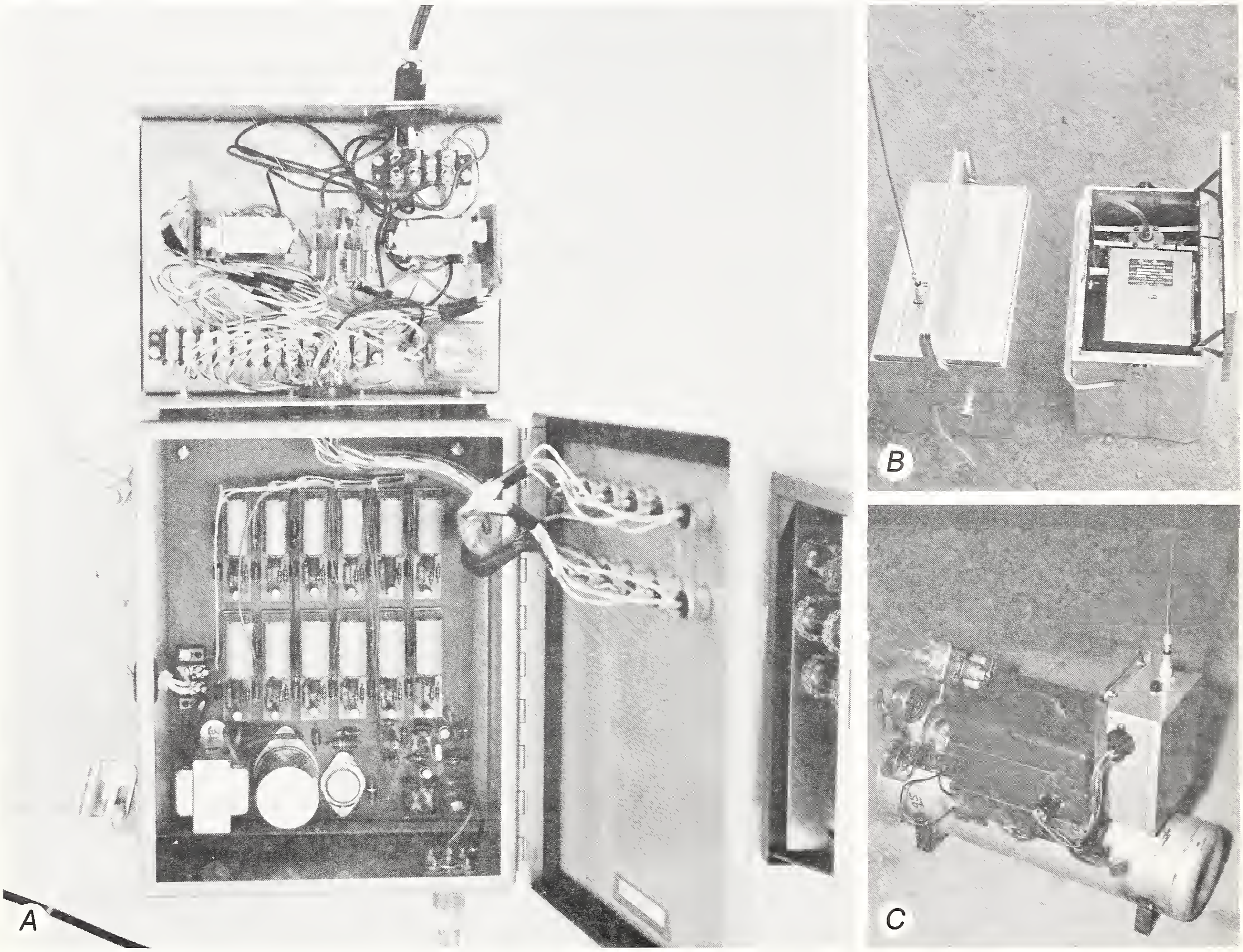


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FIGURE 37. — Radio telemetry units: *(A)* Encoder and *(B)* decoder used to remotely activate automated alfalfa valves on the Newell Experiment Station, Newell, S. Dak. The unit shown in *A* is portable but heavy because of 12-volt storage batteries required for standby power. Air pressure to operate valve is supplied from central source. Portable decoder *(C)*, pressure regulator, battery, and electric valve are mounted on portable air tank to eliminate need for field line to carry pressurized air supply.

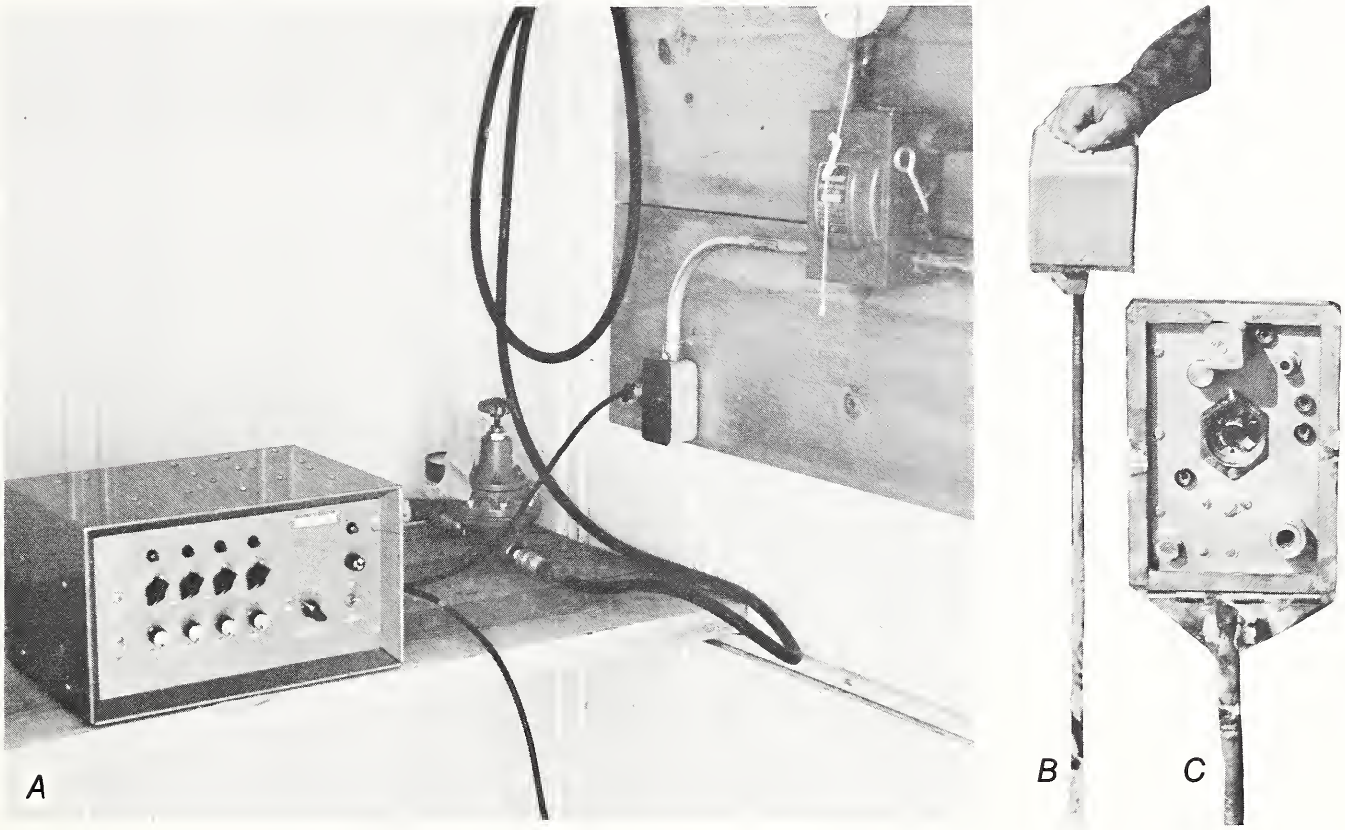

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FIGURE 38. — *(A)* A four-channel controller developed to transmit tones by wire at Wiggins, Colo. *(B)* Portable receiver is mounted on copper rod to provide a good ground. *(C)* A view of the underside of receiver shows air and electrical connectors.

constructing the controller. There seemed to be a continual need to fine-tune the output frequency of coders. Lack of response to signals by encoder at the valve to be opened sometimes caused all valves to close and standpipe to overflow, resulting in automatic shutdown of pump. These problems, however, could have been minimized with good electronic equipment.

Electronic circuits developed at the time of this demonstration appeared to be more complicated than the farmer or even trained technicians could comprehend, understand, and service. Miniature electronic circuitry now available, however, is more flexible and reliable and, if developed in quantity, can be sufficiently inexpensive that major portions of a complex circuit can be provided on plug-in boards to be replaced and discarded when failure occurs.

Mechanical Controller (Hydraulic and Pneumatic)

After our limited success with tone telemetry, we decided to investigate electromechanical controllers already developed by the turf grass industry and assorted control valves activated by either water or air pressure. With one commercially available turf system (fig. 39), plastic tubing (1/4 or 5/16 inch O.D.) is used to communicate with each automated turnout (or series of turnouts). The controller has 11 stations that can be individually set for intervals within 10-min, 60-min, and 4-½ hr ranges, depending upon the application. Accuracy of setting for longer intervals is not good, usually about 10 min. Once the controller is started, it indexes from one position to the next until all 11 stations have been

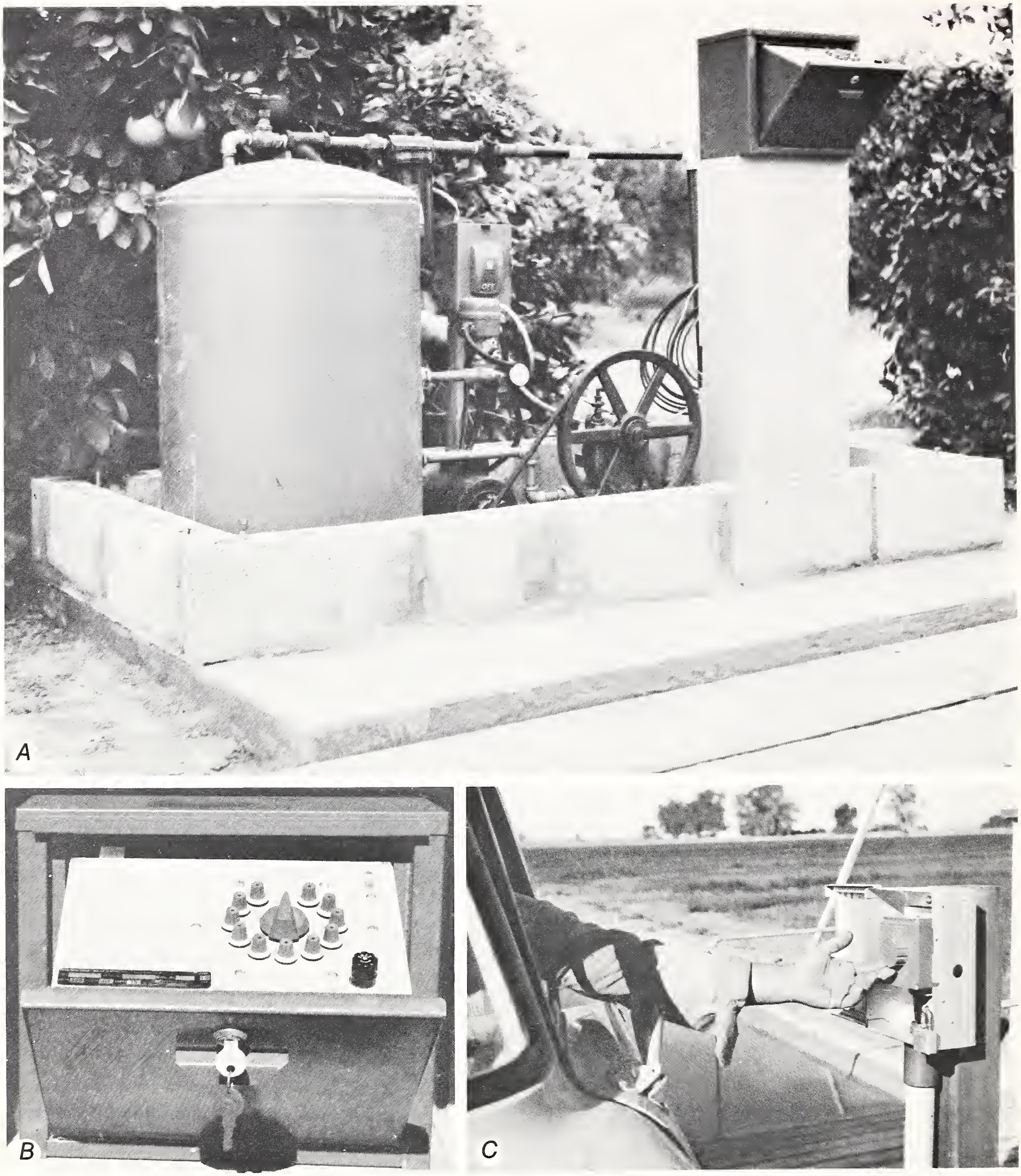

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FIGURE 39. — Control center for automated irrigation of citrus on the Yuma Mesa showing *(A)* water pressure tank and pump, and electromechanical controller; *(B)* close view of controller with 11 stations; and *(C)* same rotary three-way valve as in *(B)* but hand operated.

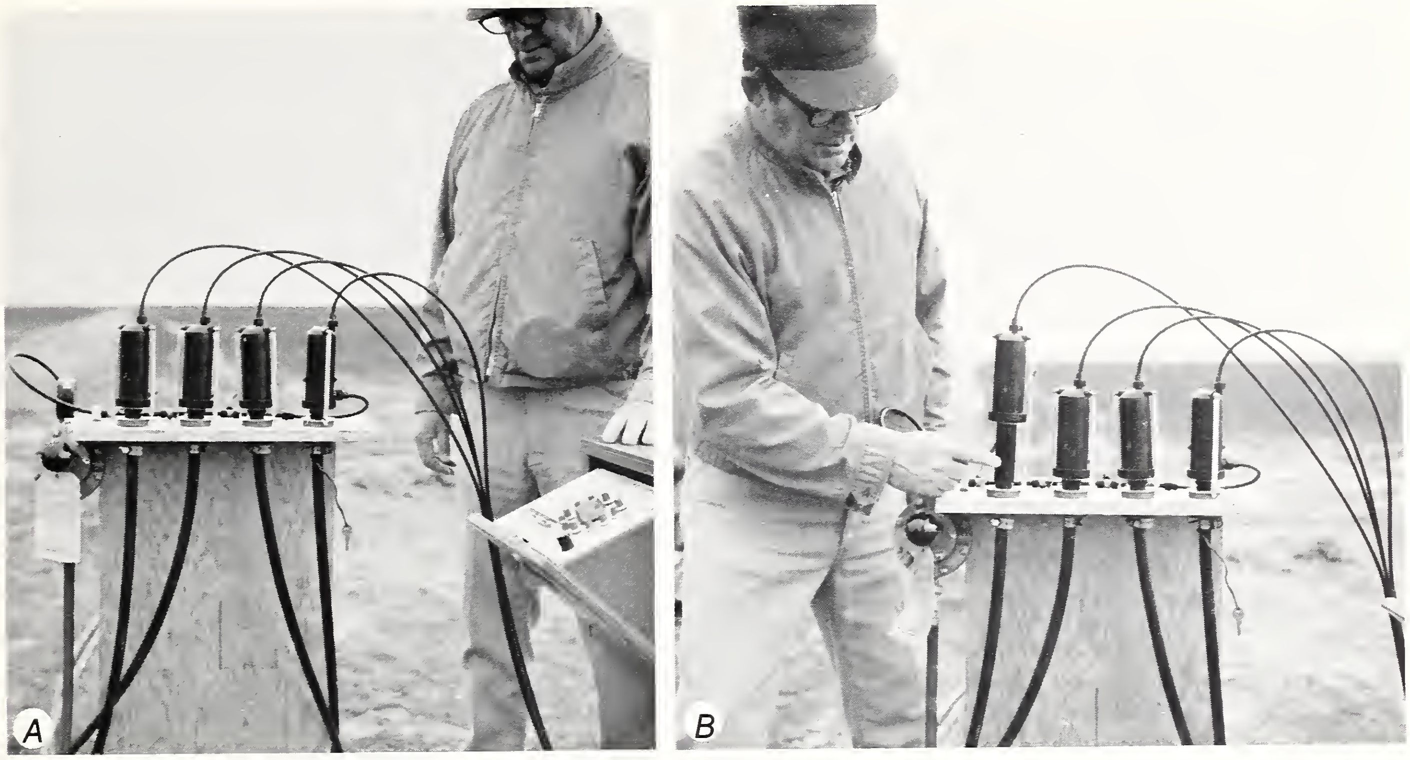

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FIGURE 40. — Modified differential area cylinder *(B)* being used as pilot valve with holes in piston wall to exhaust air rapidly. Piston at left is in open position. In photograph *(A)*, all pilot valves are closed. Small plastic lines are used between pilot valve and controller to activate piston on a preset time interval. Controller is shown at right, Bruce Church Ranch, Poston, Ariz.

activated. Skips in any one of the 11 stations can be programmed by setting that station to zero time. The controller does have the disadvantage of following a rigid sequence of operation. Erie and Dedrick (*6, 9*) partially overcame this objection with a series of quick-couple, flexible, crossover air line connections to rearrange sequences as desired.

Because of the large volume of air involved in opening and closing valves, a pilot valve for each set was made by modifying the differential area plastic cylinder (fig. 40). Using these pilot valves with the electromechanical timer provided good performance and ample adjustment for overlap of closing and opening sequences to avoid overtopping the ditch.

Although the electromechanical controller was simple and reliable, rodents frequently chewed holes in the small-diameter polyethylene communication tubing. Numerous methods of installation were tried to discourage rodent damage. Some of these schemes have been previously described. Encasing tube bundles in split PVC pipe, burying the tubes under the lip of a concrete channel lining, weighting down tubes in the bottom of a concrete channel, and, finally, simply allowing tubes to lay on the soil surface without protection were all tried with varying degrees of success.

Most of the attempts at rodent protection were on existing systems. On newly constructed, concrete-lined channels, tubes were placed in a trough formed at the upper edge on one side of the channel, as the channel was poured. It is too soon to evaluate the effectiveness of this method of protection.

In other instances, ½-inch communication tubing was used for each of the 11 stations by burying them in a trench at the top of embankment or farther into the field where periodic submergence occurs with each irrigation. Experience indicates that large-diameter tubing is not readily attacked by rodents. Gopher activity may be minimal in areas that are periodically wetted by irrigation water.

One additional possibility not explored is to encase the small-diameter tubes (or wires) in the concrete that forms the bottom or the lip of the trapezoidal section as the ditch is formed. This applies only to new construction, but it seems reasonable that spools of tubing mounted on the front of the slip form could be automatically fed into the moist concrete as the channel lining is formed. At each outlet or control

structure, special care would be needed to terminate the designated line, but once done, a high degree of permanency ought to be achieved.

Electromechanical Controller (Wire)

Electromechanical irrigation controllers utilizing individual wires for communication with solenoid valves have long been available, particularly within the turf irrigation industry. One common deficiency of this type controller is the relatively short operating cycle for which it is designed. When sprinkling turf grasses, an irrigation time on the order of one hour is usually sufficient; however, for surface irrigation, 12 hr or more per set is often required. Although electromechanical controllers are now available for agricultural applications, most such controllers cannot be programmed with the accuracy of irrigation time required, and many do not have the capability of different time of application for each irrigation set.

Solid State Electronic Controller

Recent developments in controllers have incorporated highly sophisticated electronic timers capable of activating electric solenoid control valves. These electronic timers generally have the capability of relatively long set times, yet can be set to within a minute or less of the desired time interval. These timers may be powered with 12-volt d.c. battery packs, but 110-volt supply is still needed to supply air or water pressure to activate pneumatic valves or hydraulic cylinders. One rancher near Blythe assembled a portable power package on a trailer (fig. 41*A* and *B*) using the controllers mentioned above and power supplied by a small stationary diesel engine with generator. The power unit provides energy for the air compressor mounted on the same trailer. It is pulled to and positioned on a concrete slab at the corner of the field to be irrigated. The system is manually started, and the electronic controller can be programmed to irrigate in any sequence desired. In case of controller malfunctions, replacement modules are substituted for the defective units.

H.R. Duke and M.L. Payne, in cooperation with Electronic Techniques, Inc., Fort Collins, developed a portable, single station controller particularly for use with pneumatic closures on buried pipelines (fig. 41*C*). This controller utilizes an integrated circuit clock chip to maintain a very accurate time base. This time accuracy allows the operator to synchronize the clocks on several controllers so that one will open the next irrigation set shortly before the previous set is completed. The operator thus sets each controller to the present clock time and to the times at which each irrigation is to begin, the controller sends a momentary pulse to a magnetic latching relay which opens the irrigation turnout. Upon completion of the irrigation set time, a second pulse closes the solenoid valve and repressurizes the turnout closure device. Pressure is provided at 3 to 10 psi from a portable 12-lb propane tank to which the controller and associated components are attached.

DIGITAL CONTROL SYSTEM

The most recent development is a keyboard programmable controller capable of nearly unlimited selections of irrigated blocks and sequences for outlet discharge control (fig. 42*A*). This system was developed by H.R. Duke and M.L. Payne in cooperation with Electronic Techniques, Inc., Fort Collins. Power is supplied by a 12-volt battery. One unique feature is its capability to monitor and accumulate volumes of water flowing through a measuring flume (fig. 42*B*) and to index control to next irrigation set when the preselected volume has been applied to a given area. The other feature is that only two wires are needed to transmit digitally coded signals to a large number of receivers. Each receiver (fig. 42*C*) has a capacitor and latching electric three-way solenoid valve, which is momentarily energized upon signal. Again, air or water pressure is used to operate pneumatic cylinders, pillows, convoluted cushions, or any other pneumatic or hydraulic activating mechanism devised to open and close outlet structures.

RELATED DEVELOPMENTS

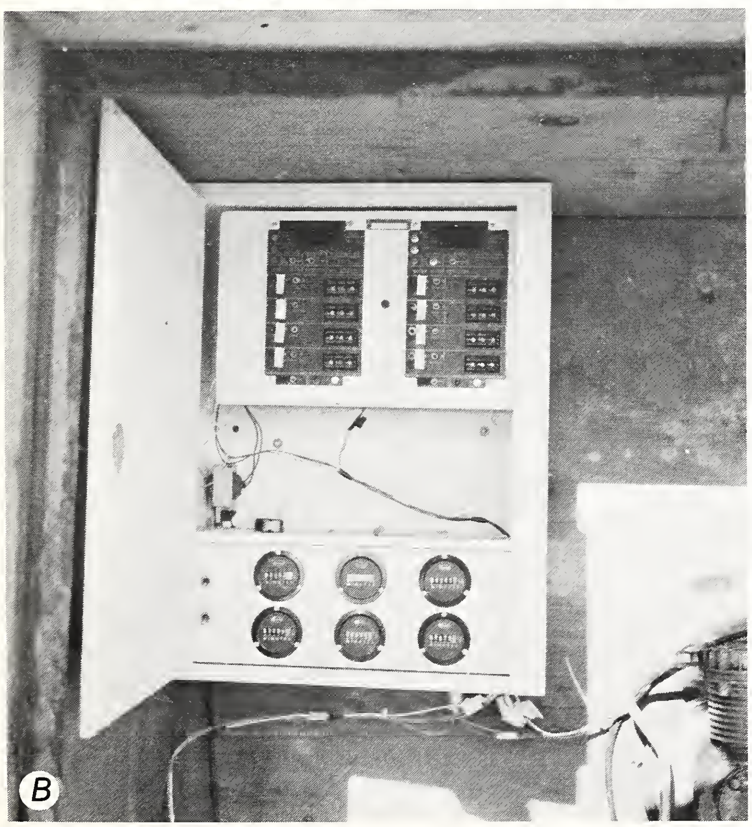
Fluidic Diverters

In the mid-1960's, we became aware of the use of fluidic devices to control and regulate flows of fluid, either gases or liquids. The science of fluidics had been largely developed since 1960, with most of the incentive for development coming from military and space exploration programs. By the mid-1960's, practical applications of fluidics included control logic ar-

rangements for machine tools and flow control for thrusters to improve maneuverability of naval vessels.

Through conversations with Peter Freeman of the Bowles Engineering Corporation, we learned that one type of fluidic element, the diverter, might be applied to control streams of irrigation water. A typical diverter (fig. 43) has the potential to switch a stream of irrigation water from one to the other of two downstream outlets, using no internal moving parts and requiring only the energy of the flowing water. The diverter utilizes a wall-attachment effect, whereby a stream or jet of fluid tends to attach itself to a wall in close proximity to the jet.

Assume flow from left to right in the diverter shown in figure 43. At the constricted section near



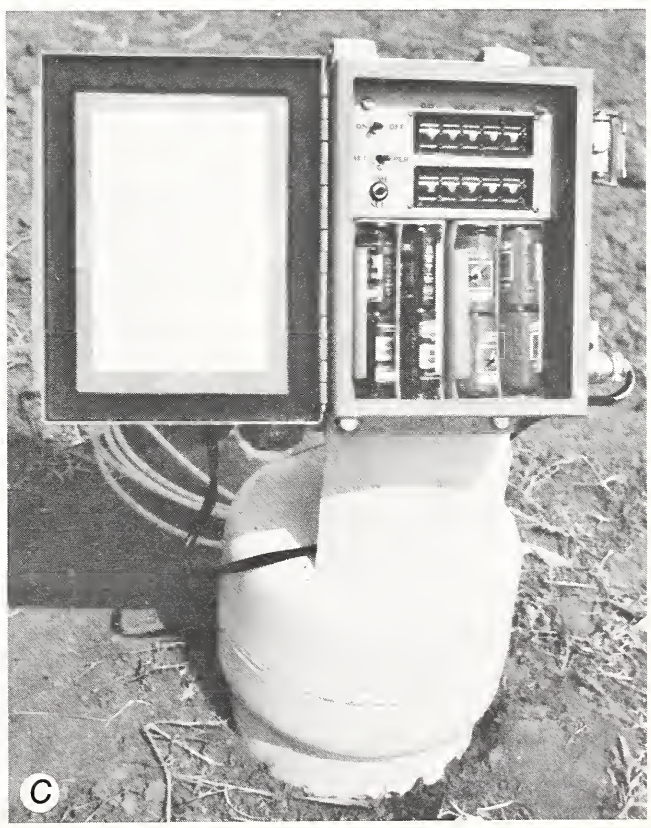


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FIGURE 41. — *(A)* Solid state controller (in white box at left) with trailer-mounted control equipment as used at Blythe, Calif. Trailer contains diesel-powered alternating current generator, air compressor, and air storage tank. *(B)* Typical solid state electronic controller capable of very precise time control. *(C)* Portable battery-powered, single station controller developed at Fort Collins.

the control port vents, velocities will be high, so pressures will be lowered, frequently to subatmospheric levels. In the diverging section immediately downstream, large eddies formed by the jet will entrain water near the sidewall, maintaining lowered pressure in these regions and causing the jet to attach to the walls. Assume that the left (upper) control port is open to the atmosphere and the right (lower) port is closed. The pressures in the region of the right control port will be more negative than at the left control port, and the jet will then attach to the right wall. The left port, being open, allows inflow of air to relieve the negative pressure on that side. Thus, a pressure differential is maintained across the jet, which continues its attachment to the right wall, and the entire flow of fluids leaves the diverter through the right downstream outlet. Closing the left control port and opening the right reverses the pressure imbalance, and the flow of fluid switches to the opposite downstream outlet.

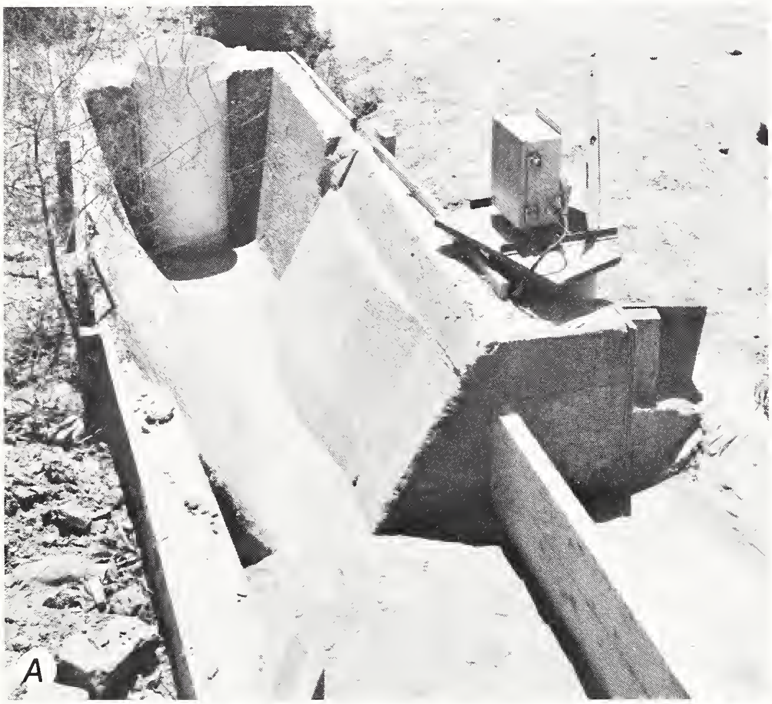

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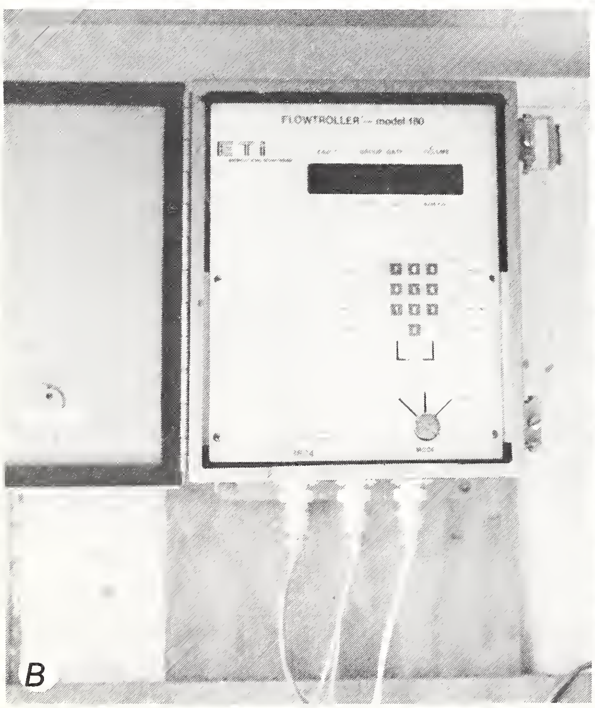
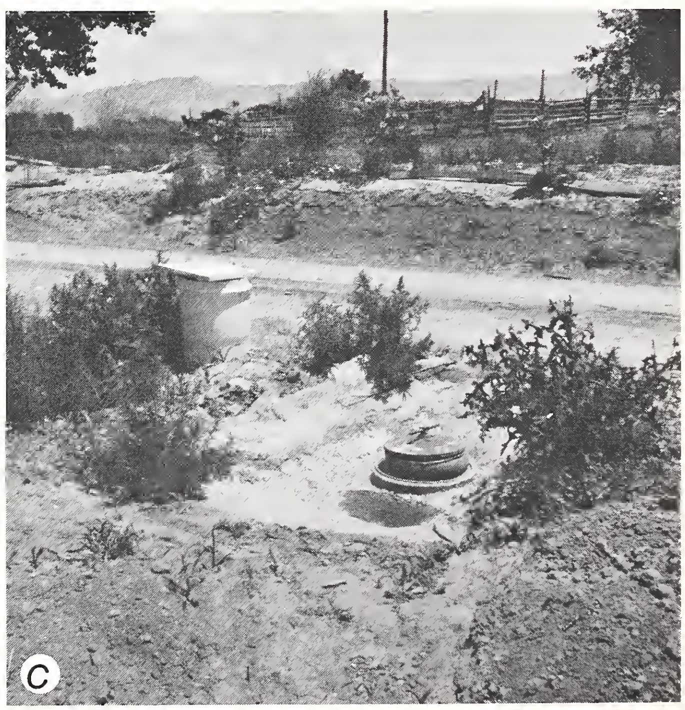
FIGURE 42.—Digital volumetric irrigation control system installed on CSU Gosnell Agricultural Research Center, Fruita, Colo., showing *(A)* water stage sensor mounted on flume stilling well, *(B)* keyboard programmable controller, and *(C)* pneumatic O-ring mounted on alfalfa riser (digital decoder and solenoid valve are inside plastic pipe section at extreme upper left of photograph).





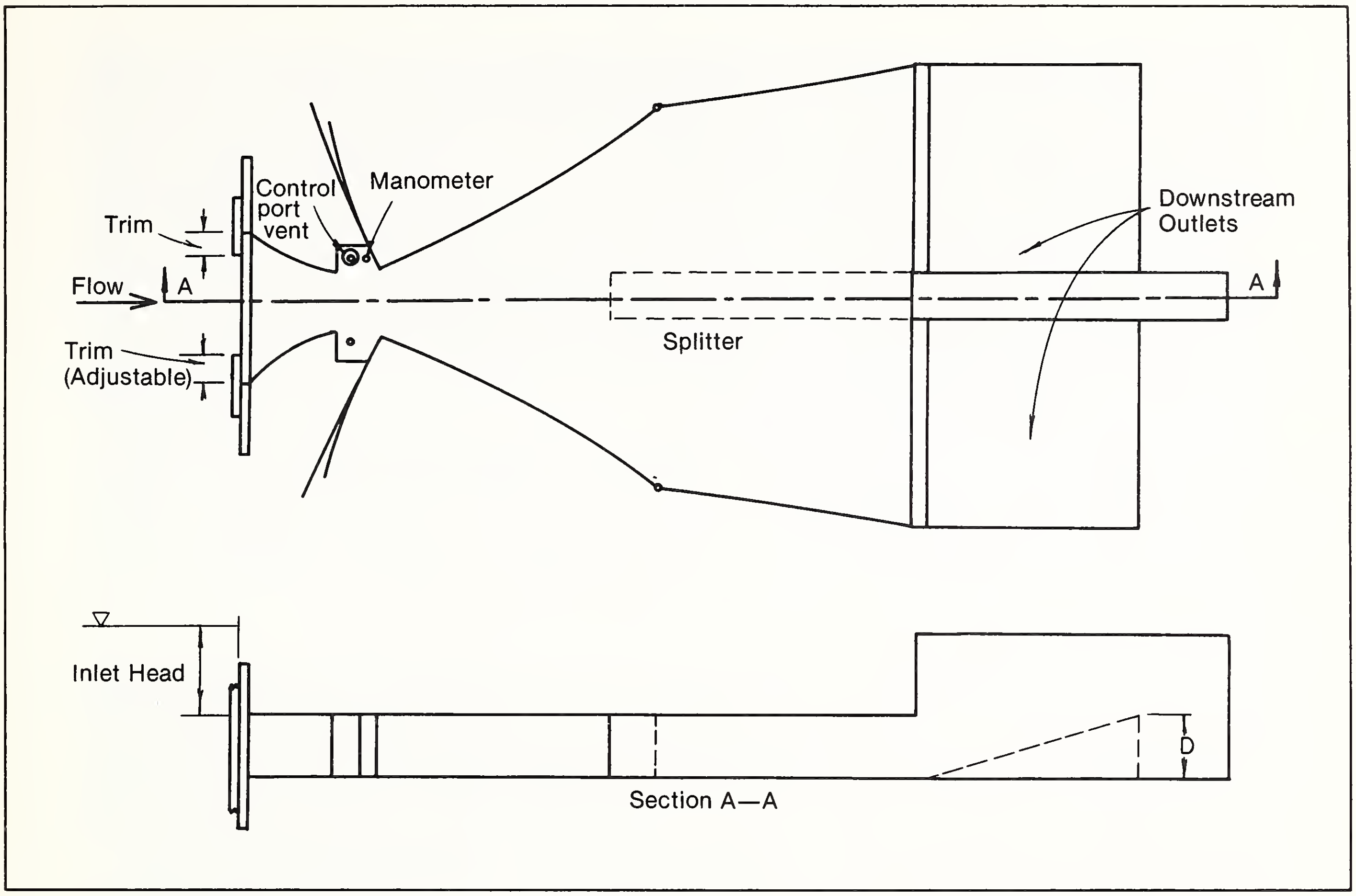


FIGURE 43. — Schematic of fluidic irrigation diverter.

Under ideal conditions of head and discharge, 100 percent of the irrigation stream can be made to emerge from one outlet with no flow from the opposite outlet. Control tubing, attached to the control port vents, can be arranged to allow remote sensing of water levels at various points on the field being irrigated, so that the flow is switched automatically to provide proper amounts of the irrigation to the sets served by one outlet of each diverter.

Control by sensing water levels has the potential advantages of (1) no outside energy requirements, such as for electromechanical controllers; and (2) control based on water advance across the field rather than elapsed time of set.

Diverters studied for switching entire irrigation streams ranged in capacity from 1.5 to 5.5 ft ^{3}/s; these units had throat cross sections of 5 by 5 inches and 8 by 8 inches. Much smaller diverters with ¼- or ½-inch throat widths were also examined as control devices for larger irrigation gates and valves. Small diverters worked properly under only a very limited range of flow rates, in much the same way as the larger diverters.

After a number of laboratory studies (fig. 44*A*) to determine the most practical construction method and materials and to determine diverter configurations and flow ranges for most reliable operation, five fiberglass diverters with 5-inch throat width were manufactured by Bowles Engineering Corporation and installed in irrigation ditches in Hawaii (fig. 44*B*).

The laboratory studies had shown that the diverters would work reliably under only a narrow range of discharge and upstream head conditions. The field installations were not satisfactory because we did not have sites with sufficient canal freeboard and with the constant flow rates required for the diverters. In addition, remote control of the diverter outlet ports required the use of fairly long lengths of small-diameter plastic tubing with the same problems of machinery and rodent damage discussed in the section: "Mechanical Controller (Hydraulic and Pneumatic)." The Hawaii sites did have adequate drop in the ditches to provide the necessary operating head for diverter operation. Head losses were appreciable through the fluidic diverters, and many sites would

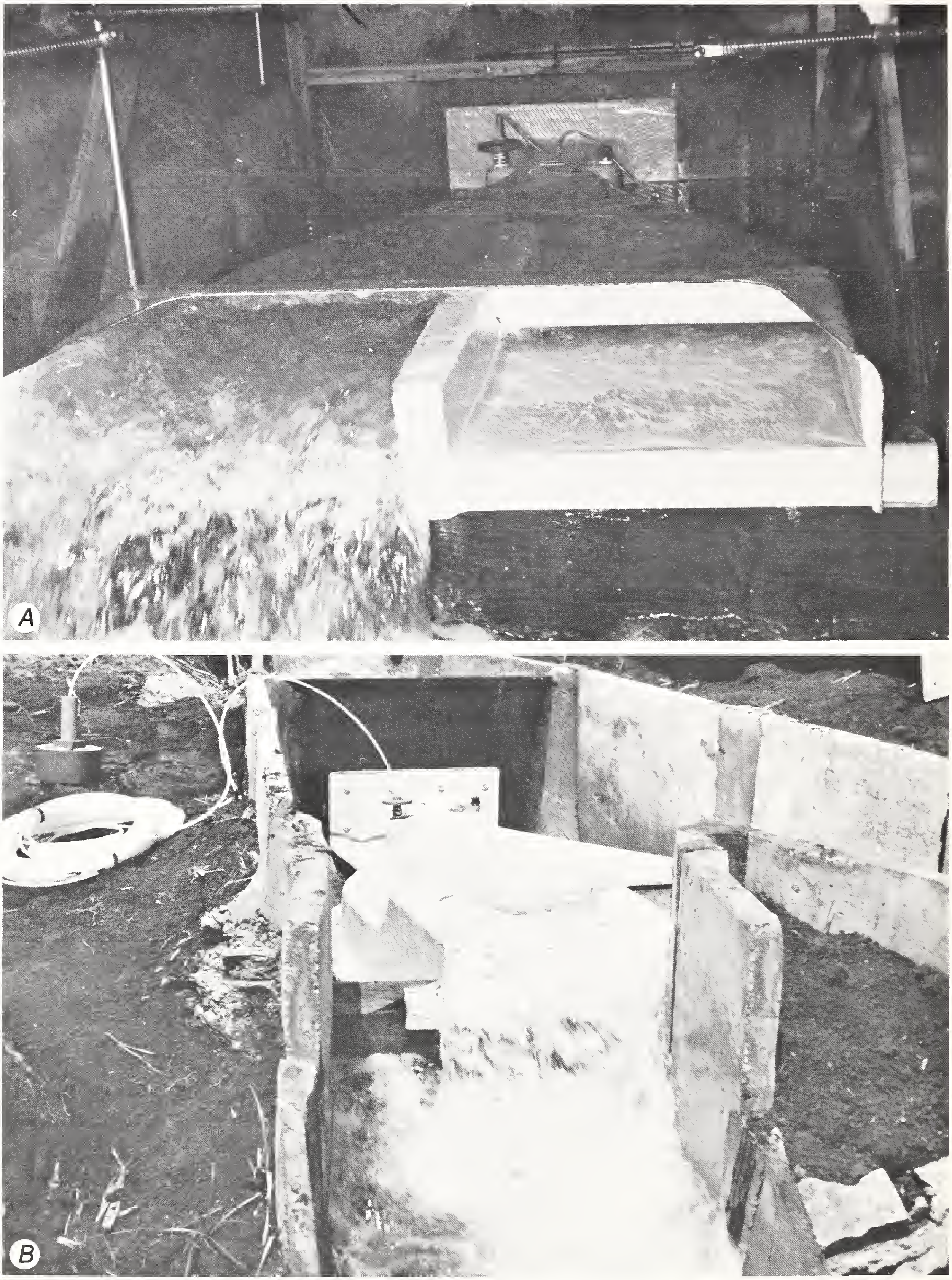


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FIGURE 44. — *(A)* The 5-inch irrigation diverter being tested in the CSU Hydraulic Laboratory at Fort Collins. Note complete diversion of irrigation stream to the left, and the still pool of water in the right outlet. ***(B)*** A 5-inch irrigation diverter installed on the Oahu Sugar Company plantation in Hawaii, at the Y-point in the Wailua flume distribution system. Note complete diversion of irrigation stream to one arm of the Wailua flume distribution system and coil of plastic control tubing connected between water presence sensor at left and throat of diverter at right.

not have adequate head available. Under sites with ideal conditions, however, the fluidic diverter does offer potential for reliable control of irrigation flows with no need for auxiliary energy sources *(47).*

Self-Closing and Regulating Valve

One of the spinoffs in development of the inflatable O-ring closure occurred while testing the small O-ring adapted to the 4-inch orchard valve in the CSU Hydraulic Laboratory. We were puzzled when the O-ring remained turgid and the valve remained closed even though air was exhausted from the rubber inner tube. The problem was traced to a leaky grommet used to join the reinforced butyl covers at the center of the valve. We discovered that water was replacing the voids between the casing and inner tube as fast as air was being released and, thus, kept the O-ring turgid and closed. Since the area of O-ring bearing surface was greater than the orchard valve outlet, the force developed kept the valve closed because of differential area even though the pressure was the same within the valve casing and pipeline.

The possibility of using this principle to develop a self-closing valve was noted, but it was not until later that the idea was further explored. All that was needed to correct the leaky grommet problem was to provide weep holes in the casing to prevent buildup of water pressure within the cover itself, so that the inner tube could perform its function.

Following development of the 2-inch pillow disk for gated pipe (fig. 35) and enlargement and adaptation to a closure for irrigation pipe turnouts, we observed how internal water pressure in a pipeline could be used to control discharge *(29).*

The self-closing valves shown in figure 45*A, B,* and *C,* utilize a rubber pillow mounted between the valve reaction plate at top and the movable disk beneath. The valve disk and pillow have an effective area about 20 percent greater than the riser opening. This differential area generates greater downward force when water pressure in the pillow and in the pipeline is the same. Thus, when pillow pressure is reduced by exhausting internal water to atmosphere, the valve opens; when water at pipeline pressure is allowed to fill the pillow, the valve closes.

A pilot valve is required for remote operation. Either air pressure valves similar to the 2-inch gated pipe valve (fig. 45*D* and *E*) or three-way electric valves can be used. Humpherys and Stacey *(42)* used electrically driven three-way pilot valves to control a similar surface irrigation pipe valve that also operated on water pressure in the pipeline.

The need for pilot valve control raises the question — why not use the communication lines directly for remote control? The choice, it seems, lies in the type of communication system selected. When air lines are used, it may be easier to use sufficiently large air lines between the valve and the controller-activated pilot valves so air can be dumped rapidly at the control center. On the other hand, locating the pilot valve at the turnout provides for rapid response time. Stringing wire to operate three-way electric valves may be more economical than installing 5/16- to 1/2-inch plastic air lines.

In some cases, the energy from water in the irrigation system can be used to modulate self-regulating valves in remote locations without electric power. Duke et al. *(8)* described a modified version of the self-closing valve that can be used in pipelines, open channels, or reservoirs. In figure 46, pressure to inflate the pillow is obtained from the static head in the supply system. The self-regulating valve automatically maintains a constant water level in a downstream basin in which an orifice or weir has been installed. A float-operated valve is provided to control flow into and out of the pillow. The manual regulating valve must be adjusted to restrict flow from the pressure source so that water will drain from the pillow when the float valve is open. Once adjusted, this regulating valve requires no further attention.

Operation of the self-regulating valve is simple. As the water level in the downstream basin rises behind the weir or orifice, the float valve begins to close. This increases pillow pressure and decreases discharge from the pillow valve. Conversely, as the water level recedes in downstream basin, the float valve opens to discharge from both the pressure source and pillow. Figure 47 illustrates the performance of the valve shown in figure 46*C* and *D.*

Uses for the self-regulating valve include control of water level in a downstream basin, control of discharge from a reservoir, and control of discharge from canals into farm laterals. Minimum head required is 0.5 ft.

Self-Propelled Ditch Irrigator

In the mid-1960's, the Farmhand Corporation was marketing a self-propelled irrigator with the trade name Powerdike. This machine consisted of a framework supported by a single axle and two drive wheels that straddled a small irrigation ditch and a "bullet" at the front end of the machine that rested in the ditch bottom to guide the machine along the ditch contours. A small gasoline engine propelled the ma-

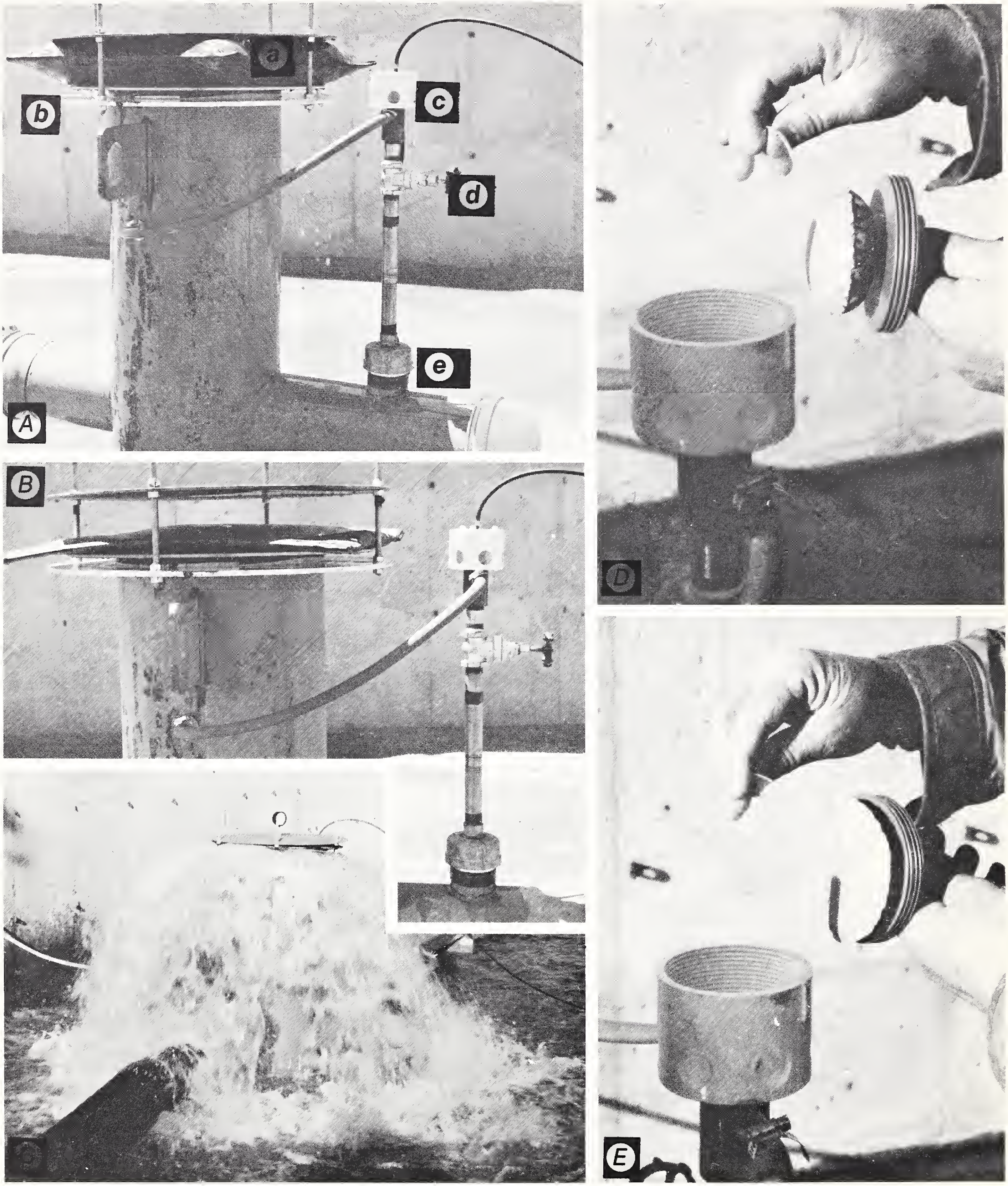

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FIGURE 45. — *(A)* Self-closing valve with pillow *(a)* inflated by water pressure in pipe. Inflated valve forces closing disk *(b)* against valve seat. Pilot valve *(c)* and regulating valve *(d)* control waterflow to pillow from Pitot tube *(e)* in line from reservoir. *(B)* Pillow deflated (valve open) and *(C)* water flowing. Disassembled pilot valve *(C)* with pilot pillow inflated *(D)* and deflated *(E)*.

chine very slowly along the ditch. A flexible dam supported near the rear axle ponded water behind the Powerdike and caused it to overflow the lower ditchbank, flooding the land below the ditch. One of the principal objections to the Powerdike was that ditchbanks eroded when overtopped. A CSU graduate student, Allen Rider,[7] modified the Powerdike (fig. 48), incorporating the basic Powerdike framework and propulsion system, but with mechanisms to lift water over the ditchbank to the land to be irrigated.

[7]Rider, A. R. Pump characteristics of a screw conveyor used on an automatic irrigator. Master of Science Thesis, Colorado State University, 85 p. 1966. [Mimeographed.]

OUTLOOK FOR AUTOMATION

Although available figures do not allow us to give a precise breakdown by type of surface system, the 1978 Irrigation Journal survey indicates the 37 million acres irrigated by surface methods in the

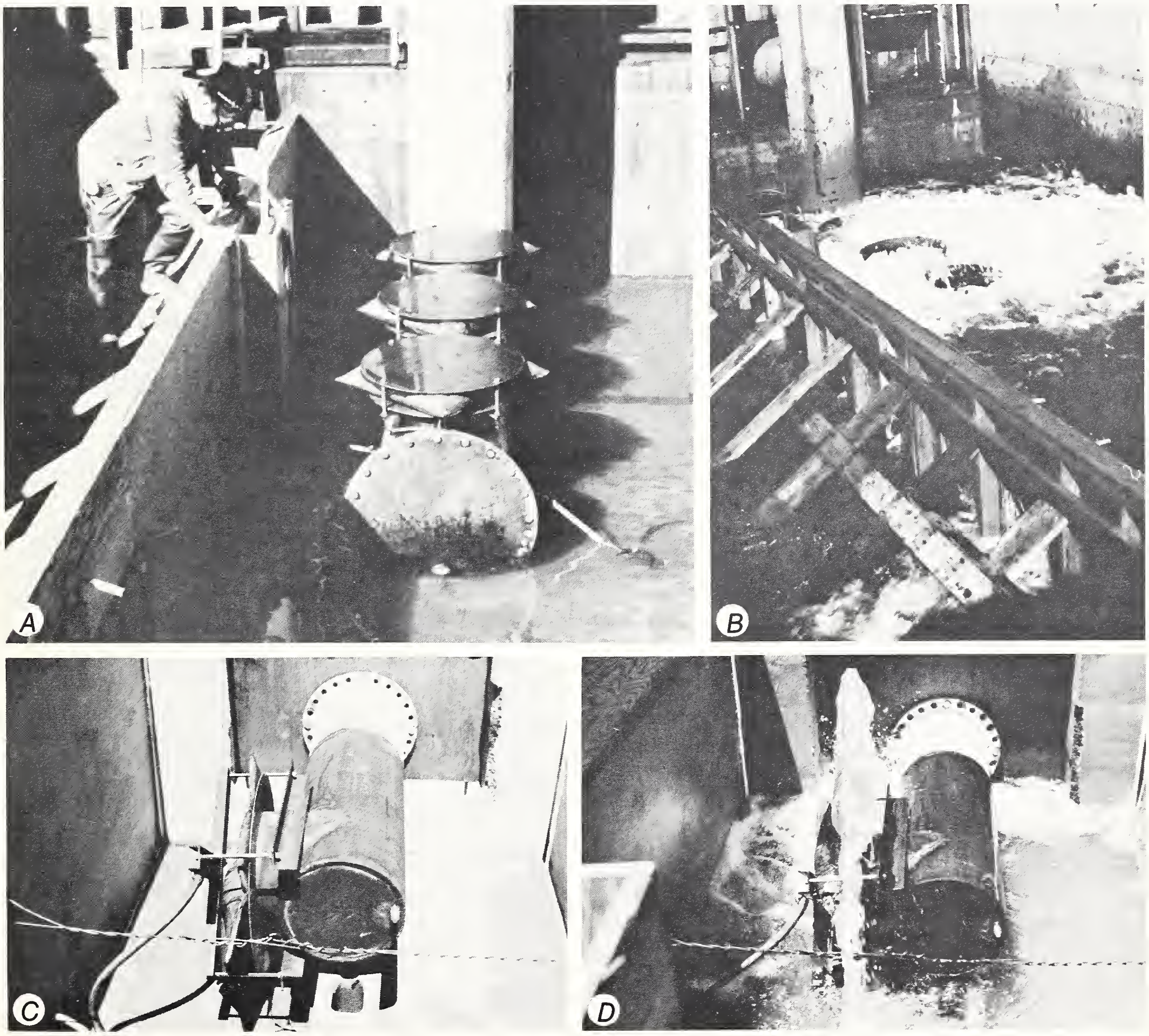

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FIGURE 46.—Self-regulating constant-discharge valve. Large manifolded valves (*A* and *B*) are capable of high, controlled flow rates, but the upright configuration required a minimum differential head of 4 ft to maintain control. Same type of valve *(C)* on side outlet discharges 5 ft^3/s *(D)* at 0.5 ft head differential. Side outlet configuration allows discharge regulation with low head differential.

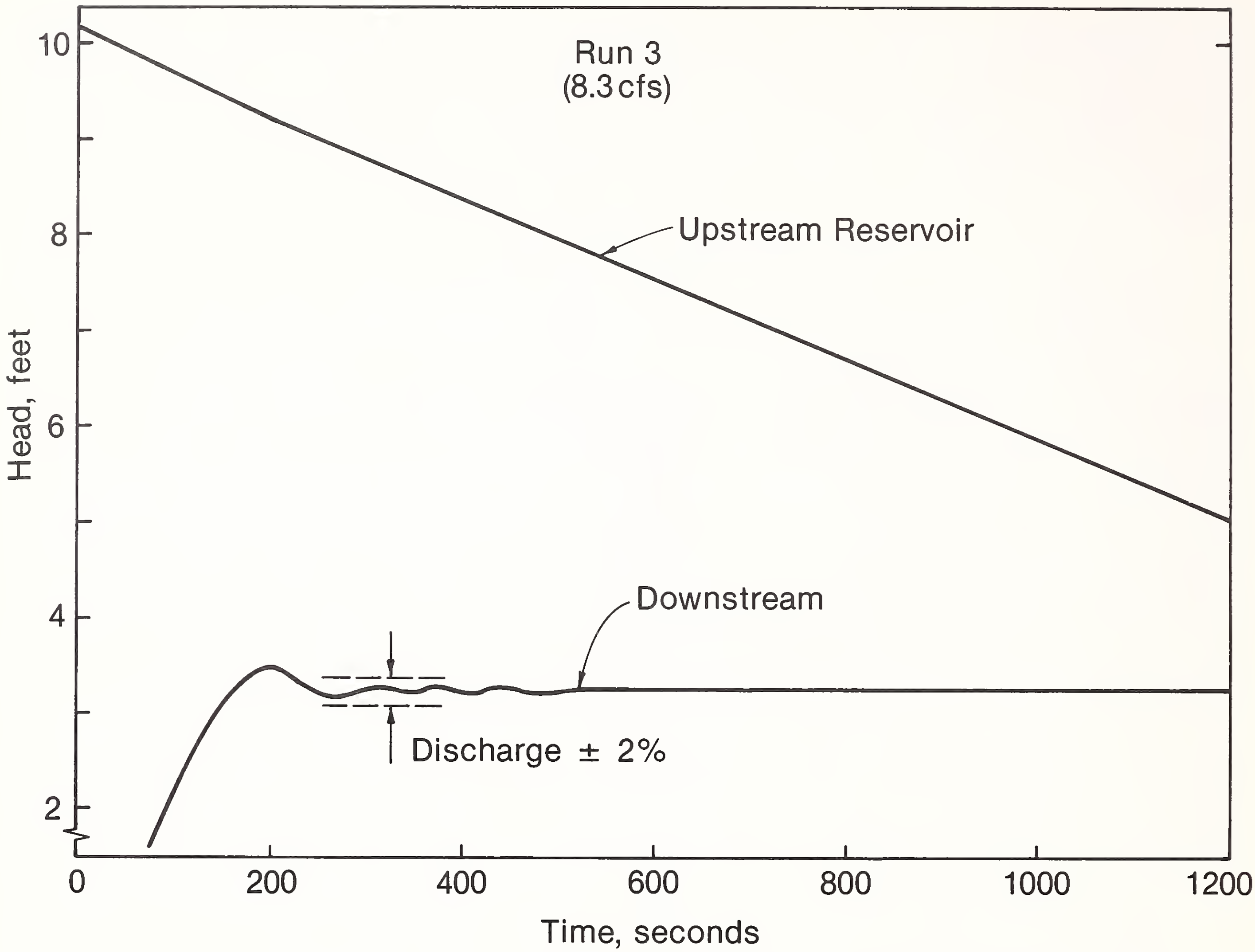

FIGURE 47. — Typical results of laboratory experiments with self-regulating constant-discharge valve. After initial startup (about 4 min), discharge was controlled within ± 2 percent over a wide range of upstream head.

West include approximately 4 million acres using underground transmission pipe and 9 million acres using gated surface pipe from the water source. The remainder is irrigated from open ditches. Potential exists for more widespread automation of all these surface irrigation systems.

The potential benefits from automation of surface irrigation are many. The typical irrigation farmers often use other than optimum stream sizes and irrigation set times to achieve a convenient irrigation schedule. As a result, irrigation application efficiencies are lower than they could be with carefully designed stream size and set time. Inefficiency is also the result of human errors. Particularly where large flow rates are used, a few minutes error in changing a set can amount to a substantial percentage error in water application. With reliable automation, precise set changes can eliminate the consequences of poor management.

The efficiency that can be achieved by automation was illustrated by field measurements with gated pipe systems by Fischbach et al. *(13)* and on level basins by L. J. Erie (personal communication), who reported uniformities in excess of 90 percent. Two factors are important in systems with large flow rates per unit area: Water must be applied for precise lengths of time, and the field must be perfectly level. The success of Erie and Dedrick's Arizona automation proves the first can be accomplished. Adaptation of the laser for field leveling has made practical the precise leveling of large acreages. The laser-controlled scraper provides consistent land forming over 40-acre fields to within ±0.05 foot with no surveying.

FIGURE 48. — Automatic self-propelled contour ditch irrigator. This machine consists of a commercially available Powerdike modified to pump water over the ditchbank while traveling slowly along the ditch, dragging a flexible dam to pond water to supply the pump inlet.

Maintenance of high efficiencies enhances protection of the environment by reducing leaching of salts and applied fertilizers, controlling tailwater runoff, and reducing subsurface drainage problems. Although the water lost to crop use by inefficient application represents a direct energy cost in areas where water is pumped, other energy-related costs are probably more significant. Energy input to leached fertilizer can be large. The largest potential for energy consumption, however, comes from conversion to sprinkler irrigation to obtain automation. If an average of 18 inches of water is pumped annually, the energy consumption to pressurize to 60 psi for sprinkler irrigation (that is, above that required to deliver water to the surface) amounts to about 325 kWh per acre annually.

Although many factors may prompt the farmer to seek irrigation automation, the most prominent is labor. The shortage of farm laborers, as well as growing demands of organized farm labor, forces the farmer to seek other means of irrigation.

Throughout the years of our research on irrigation automation, we have been continually urged by irrigators to develop the ultimate in automation, convenience, and reliability. During the early years, systems installed in the field were invariably met with initial enthusiasm, which gradually diminished to the point that the automatic systems were abandoned. At that time, when many components were only available from our shop, such a fate should have been expected.

By the time we installed the pipe outlet closures and jack-gate turnouts in the desert Southwest, almost all components were available (some by special order) from commercial suppliers. Yet we continued to see these systems deteriorate after being turned over to farmers for operation and maintenance. Many farmers seem to view the irrigator as the worker they can best afford to pay to carry a shovel and wade in the mud, and this is the worker who is assigned to operate an automated system. Even though the automated irrigation system represents a substantial equipment investment (our target has been on the order of $100 per acre), those farmers who abandoned the systems do not seem to recognize that this system needs and deserves the same care and maintenance as their other farm machinery. We have observed bent and battered gates, long-neglected seals, and parts corroded beyond usefulness due to lack of periodic maintenance. Until and unless farmers are willing to assign responsible personnel with some mechanical aptitude to operate the irrigation system and are willing to devote reasonable time and money to maintenance and protection of their investment, they must resign themselves to irrigation with manual labor.

Farm acceptance and confidence in these automated irrigation systems remain high largely due to the efforts of Erie and Dedrick in installing and training operators in the Wellton-Mohawk project in Arizona. During a recent visit of the senior author, one system was irrigating at the rate of about 15 ft^3/s, changing sets every half hour or so, with no irrigator present — proof that these irrigation systems can be reliable.

Further evidence of the acceptance of automation is the fact that in 1977 the USDA Soil Conservation Service approved a cost-sharing program for installing these systems in the Wellton-Mohawk project area. In a program begun in 1979, the USDA Agricultural Stabilization and Conservation Service required automation as a condition for cost sharing on-farm improvements in the Grand Valley of Colorado.

As of this writing, valves for underground pipe are available commercially from at least three companies, and a few other components are beginning to become available. As higher costs of energy and labor force farmers to adopt more efficient water management practices, the commercial availability of automatic systems will undoubtedly grow with production volume. Molding the modified pillow for the

USDA valve from newer thermoplastics could greatly reduce costs and improve durability.

Throughout this paper, we have referred to the irrigation components developed as automatic systems. We must concede that the systems considered to date switch irrigations by remote control, whereas true automation requires no immediate human decision. The key to development of truly automatic equipment is undoubtedly solid state electronics.

Irrigation controllers, pump monitors, and many other instruments for agriculture are now being designed with low-cost, reliable, solid state electronic components. Dedicated microprocessor units are available to process climatic data for prediction of plant disease problems. Research is underway at several locations to develop units for computing evapotranspiration. Digital radio frequency transmission makes reliable remote sensing of data feasible. Someday, such instruments may monitor the farmers' fields and "decide" when to irrigate based on ET calculations, then start the irrigation, measure the amount applied, and change to the next set — a truly automatic system.

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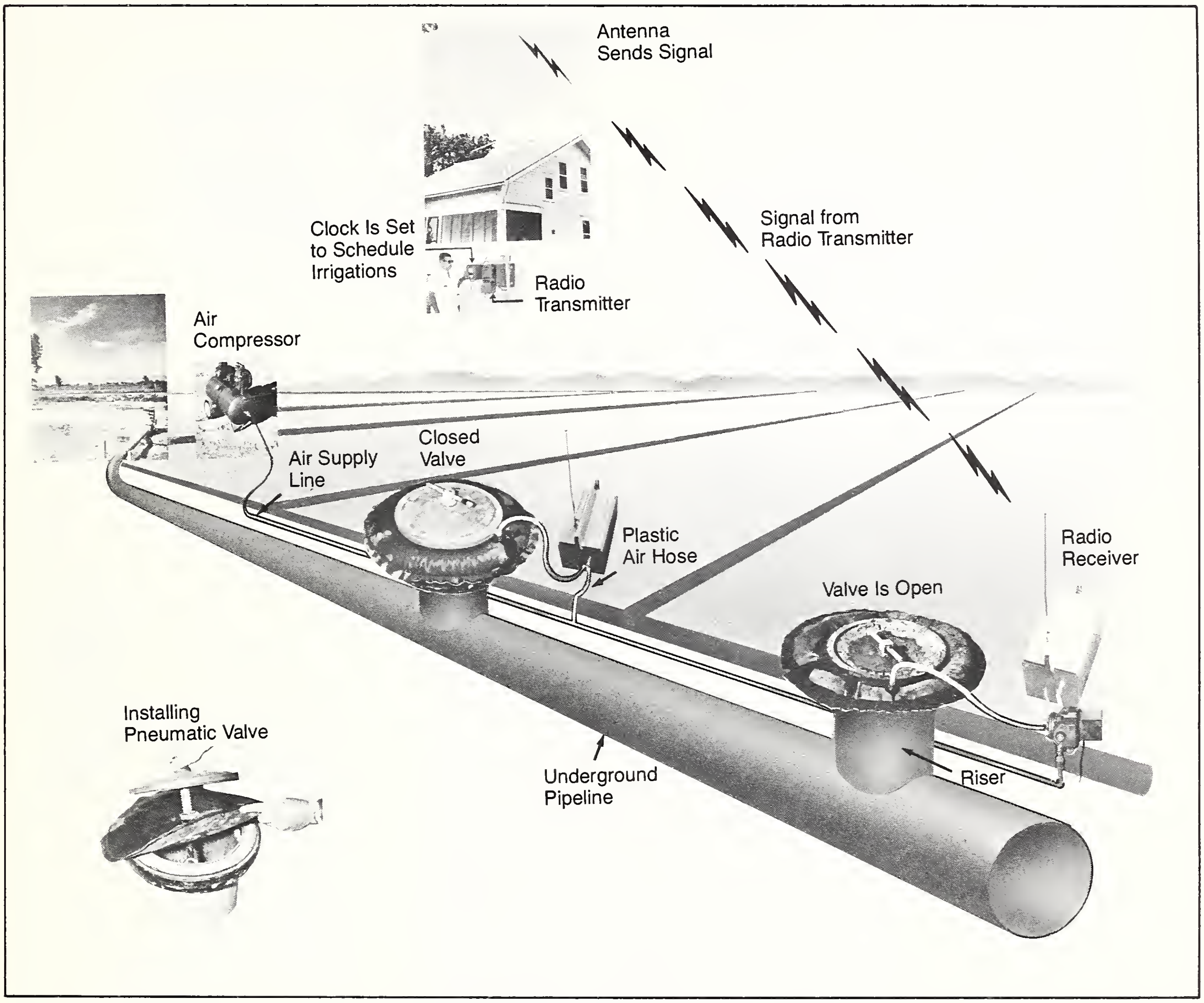
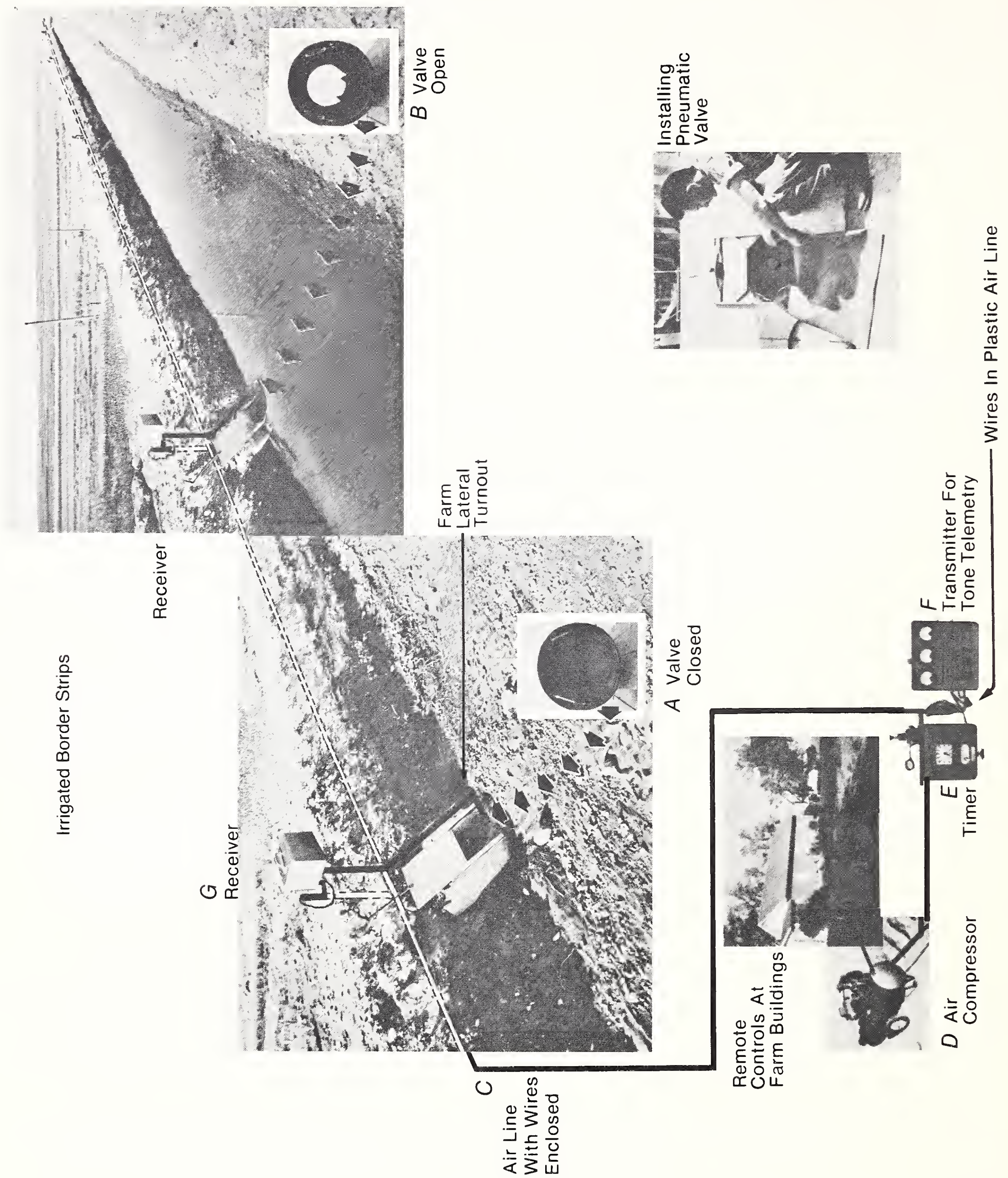
APPENDIX FIGURES
(Operational Details of Selected Surface Automation Systems)



Appendix figure 1. — Overall operation at Newell, S. Dak., of a radio tone controlled automated pipeline irrigation system: Installation of pneumatic valve (lower left); open USDA valve (lower right); closed USDA valve, inflated (center); air compressor and well pump (far left); radio signaling equipment and timer (top); and receivers tuned to corresponding channel at right of each valve on pipeline. Momentarily energized solenoid valve, actuated by 12-volt battery and condenser, inflates or deflates pneumatic valve to control discharge of irrigation water.

The pneumatic diaphragm is held in position by a centrally located metal sleeve capable of sliding up and down the threaded screw supporting the valve lid. In an open position, the diaphragm is forced against the bottom of the valve lid and appears to ride on top of the water flowing from the alfalfa valve. In an inflated or closed position, the diaphragm forms an annular seal against the valve seat and valve lid. About 5 to 10 psi of air pressure in the pneumatic diaphragm is sufficient for most pipeline distribution systems (patented by H. R. Haise and E. G. Kruse, May 23, 1967, as a public USDA patent).



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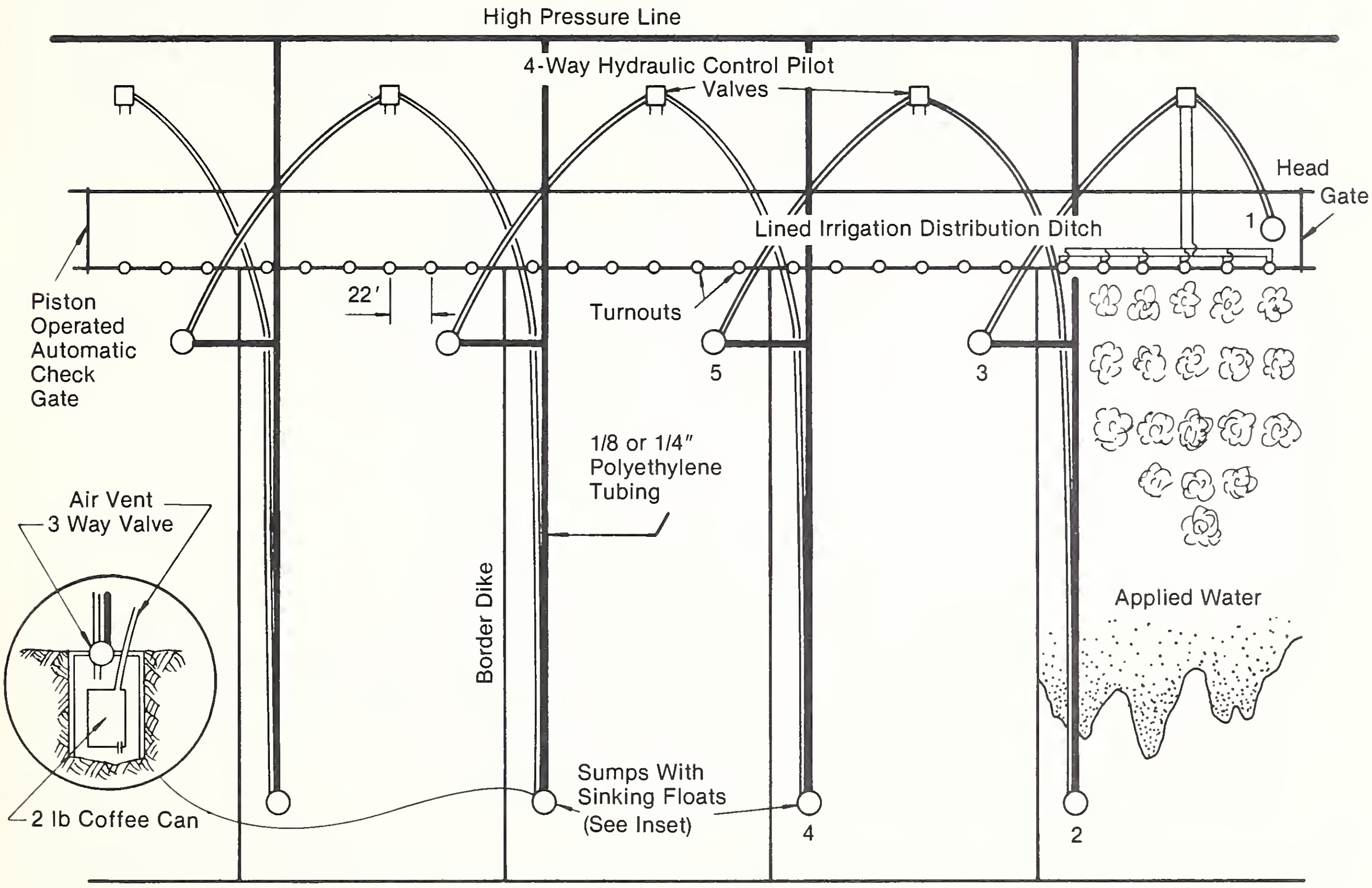
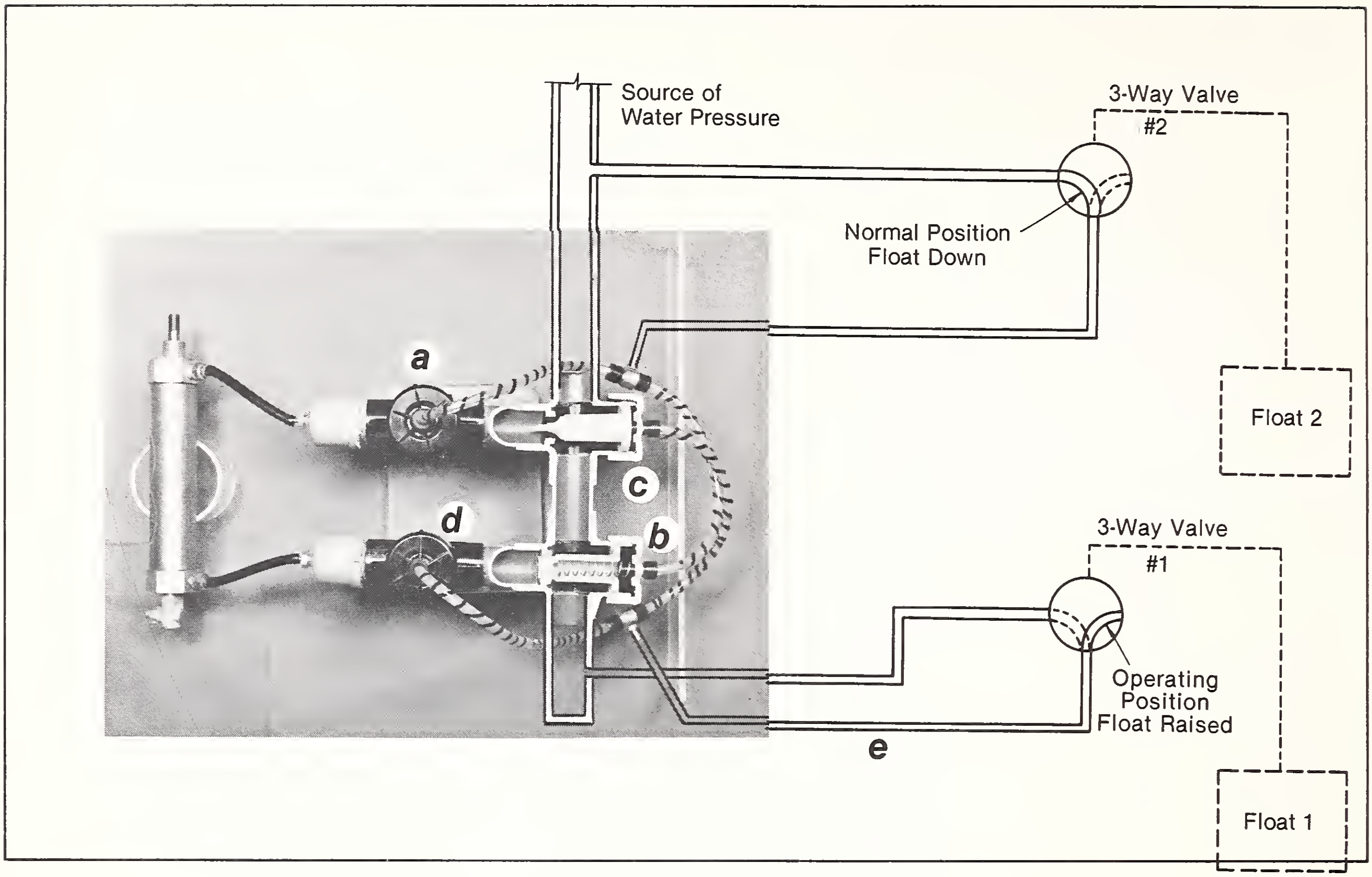
Appendix figure 2. — Lay-flat valves installed in pipe turnouts on unlined farm lateral on Seedskadee Development Farm in western Wyoming. Insets show pneumatic lay-flat valve inflated (turnout closed) *(A)* and deflated *(B)* to allow flow to occur. Air supply to valves is supplied by central compressor *(D)* and distributed by buried plastic pipe. Control system consists of timer *(E)* and tone telemetry transmitter *(F)*, which signals any one of 12 receivers *(G)* independently.



Appendix figure 3. — Automatic surface irrigation adapted to 10 acres of citrus grown on the Yuma Mesa, Ariz. Sequence of operation is as follows: *(1)* Headgate is opened; *(2)* water fills concrete-lined irrigation distribution ditch and overflows sump 1, which hydraulically activates four-way pilot valve (see Appendix fig. 4), opening first set of six turnout gates; and *(3)* water flows between border dikes of first irrigation set to sump 2. Inflow of water here causes three-way valve to actuate second four-way pilot valve (second from right), causing second set of six turnout gates to open; *(4)* water flowing through turnouts enters sump 3 of six gates; and *(5)* water flows between border dikes to sump 4, which actuates the four-way pilot valve (third from right), opening the third set of six turnout gates. Sequence is repeated until entire block is irrigated and automatic check gate (far upper left) releases water to the next 10-acre block to be irrigated. Pilot valves are connected to sump valves by ¼-inch polyethylene hydraulic communication tubes.



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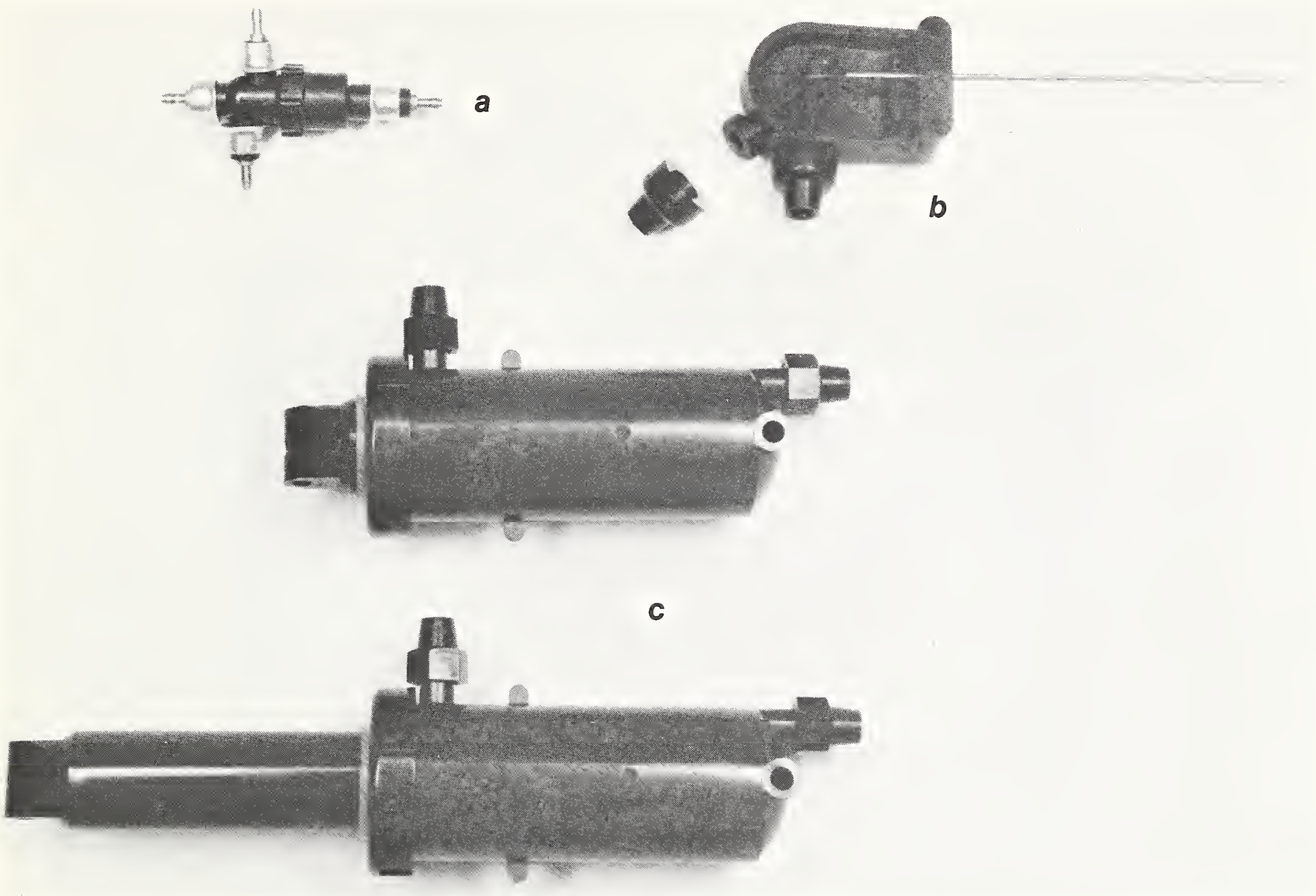
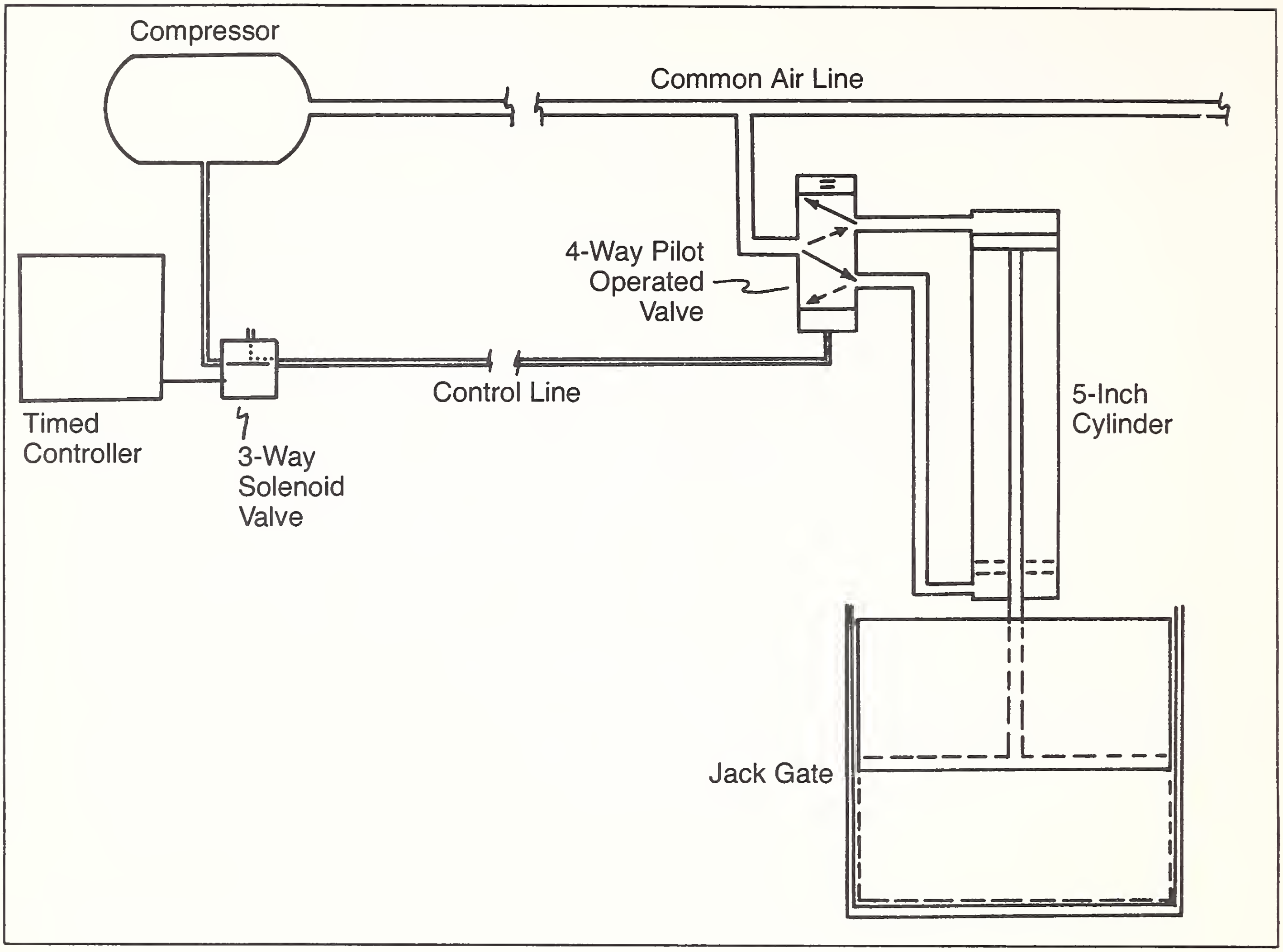
Appendix figure 4. — The hydraulically actuated four-way pilot valve shown here is capable of being remotely operated by surface water sensors to activate water cylinders connected to gates, checks, or valves. The system of operation is as follows: When water enters the sump (corresponding to sumps 1, 2, 4, and so on in Appendix fig. 3*a*), float 1 raises, moving valve 1 to operating position. Pressure in line *E* is lowered to atmospheric, allowing valves *C* and *D* to open. Valve *C* allows line pressure to retract cylinder (as shown), opening gate. Spent water is wasted through valve *D*. In a few minutes, float 1 sinks, repressurizing line *E* and closing valves *C* and *D*; the gate remains open. When water enters the next border, indicating the next group of gates has opened, it enters the sump at float 2 (sumps 3, 5, and so on in Appendix fig. 3*a*), operating valve 2 and opening valves *A* and *B*. Cylinder is extended, closing gate to shut off water to field. Float 2 soon sinks. Floats and wells drain between irrigations, providing automatic reset for next irrigation.



PN-6733

Appendix figure 5. — Commercial plastic components for automating surface irrigation systems including *(A)* three-way pilot valve, *(B)* three-way float valve, and *(C)* differential area hydraulic cylinder. *(A)* The three-way pilot valve is used at the end of long plastic communication lines to reduce time required to open gates. Manifold connected to six hydraulic cylinders, for example, can be connected directly to this three-way valve to permit rapid activation of butterfly gates. The water-filled communication line merely transmits pressure to operate three-way valve without flow of water and regardless of length, within practical limits. *(B)* The three-way float valve is used in sumps described in Appendix figure 3*a*. The differential area hydraulic cylinder allows three-way operation. With equal pressure supplied at top and end ports, the piston rod will extend because the area at bottom of the piston is almost double that of the rod itself; therefore, in this mode, water is forced back into water pressure supply system as the piston extends. When the port at right is vented to the atmosphere, ambient water pressure at the top port causes the piston to retract.



Appendix figure 6. — First automated irrigation system using jack-gate turnouts installed near Blythe, Calif. Operating pressure is supplied by the compressor to all four-way pilot valves by way of the ¾-inch air line. In the unenergized state, the top of the jack-gate actuating cylinder is connected to the common air line, and the bottom of the cylinder is vented to atmosphere, which keeps the jack-gate closed. Upon a signal from the controller, the three-way solenoid valve shifts, pressurizing the control line. Pressurization of the pilot on the four-way valve shifts this valve to vent the top of the cylinder and pressurize the bottom, thus raising the jack-gate.

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